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NISTIR 6566

Workshop on Temperature Measurement of Semiconductor Wafers Using Thermocouples

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January 5, 2001

U.S. DEPARTMENT OF COMMERCE
Norman Y. Mineta, Secretary

TECHNOLOGY ADMINISTRATION
Dr. Cheryl L. Shavers, Under Secretary
of Commerce for Technology

NATIONAL INSTITUTE OF STANDARDS
AND TECHNOLOGY
Dr. Karen H. Brown, Acting Director

Workshop on

Temperature Measurement of Semiconductor Wafers Using Thermocouples

K.G. Kreider, D.P. DeWitt, B.K. Tsai
National Institute of Standards and Technology
Gaithersburg, MD

and

B. Lojek
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Colorado Springs, CO

September 19, 2000
NIST, Gaithersburg, MD

A satellite workshop held at NIST conducted in collaboration with the 8th International Conference on Advanced Thermal Processing of Semiconductors - RTP'2000.

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National Institute of Standards and Technology
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Summary of the Workshop

RTP'2000 is a conference for engineers, scientists, managers, and marketing specialists working in the thermal processing of semiconductors, manufacturing, simulation, and equipment development. The goal is to provide a comprehensive overview of current and future directions of thermal processing technology and processing systems. The primary emphasis is on the state-of-the-art tools, and on rapid thermal processing (RTP) and furnace concepts and methods as they apply to commercial Ultra Large Scale Integration (ULSI) processing.

Temperature measurement is an important parameter in most semiconductor processes. These measurements are necessary in temperature ranges as low as below 0°C in some plasma etch processes, to near room temperature for soft bakes of resists, to 500 °C for low temperature chemical vapor deposition (CVD) and sputter deposition, and all the way up to 1150 °C for oxidation. Accurate temperature measurements are needed to control the quality of the wafer processing. Although non-contact temperature measurements have advantages on the processing tools, these techniques must be calibrated by running expensive test wafers or by comparison with contact sensors. The thermocouple can be a very useful sensor when calibrated on an international temperature scale such as the International Temperature Scale of 1990 (ITS-90). In this workshop, we will describe how to use thermocouples for measurements of temperature in semiconductor processing and how to achieve the highest accuracy.

Our workshop will begin with a presentation by Dr. Dean Ripple, Group Leader for the Thermometry Group at the National Institute of Standards and Technology (NIST). He will first describe the temperature scale, uncertainty, and traceability. Then he will discuss the use of thermocouples and thermocouple wires. Dr. Ken Kreider will follow with a talk on surface temperature measurement, and Dr. David DeWitt will present an explanation of the relationships between thermocouples and radiation temperature measurements.

Bruce Adams of Applied Materials will describe his experience in the use of thermocouples and radiation thermometers in measuring temperature in rapid thermal processing. Karl Williams of Silicon Valley Group, Thermal Systems Division, will discuss the thermal characterization of batch furnaces using thermocouple instrumented wafers. The final talks will be presented by Bakul Damle of National Instruments and Tom Hayden of Keithley Instruments on instrumentation issues. A panel, moderated by Dr. David DeWitt, will feature brief presentations by Tony Fiory, Lucent Technologies, Inc., and Jeff Gelpey, Steag RTP Systems, and will address issues of concern to the workshop.

B.K. Tsai, Editor

K.G. Kreider
D.P. DeWitt
B. Lojek

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Jeff Gelpey, Steag RTP Systems

Workshop Program

Morning Session - Fundamentals of Temperature Measurements

9:00 - 9:15	*Welcome, Introductions and Overview* - Ken Kreider, NIST
9:15 - 10:00	*Temperature Scales, Uncertainty, and Traceability* - Dean Ripple, NIST
Break	
10:15 - 11:00	*Thermocouples and Thermocouple Wires* - Dean Ripple, NIST
11:00 - 11:30	*Surface Temperature Measurements* - Ken Kreider, NIST
11:30 - 12:00	*Relationship between TCs and RT Measurements* - Dave DeWitt, NIST
12:00 - 12:30	*RTA T/C and RT Measurements* - B.E. Adams, Applied Materials
Lunch	

Afternoon Session - Applications of Temperature Measurements

1:30 - 2:15	*Measurement of Wafer Surface Temperature using Thermocouples and Temperature Calibration of RTP Equipment* B. Lojek, ATMEL Corporation
2:15 - 3:00	*Thermal Characterization of Batch Furnaces using Thermocouple Instrumented Wafers,* Cole Porter and Karl Williams, Silicon Valley Group, Thermal Systems Division
3:00 - 3:25	*Computer-Based Temperature Measurement Systems* Bakul Damle, National Instruments
3:25 - 3:45	*Instrumentation Issues for Thermocouple Measurements* Tom Hayden, Keithley Instruments
Break	
4:00 - 5:00	*Participants' Questions - Panelists* and Speakers* – Dave DeWitt, Moderator (* Provided 5-7 minutes for presentations) A.T. Fiory, Lucent Technologies, Inc. Jeff Gelpey, Steag RTP Systems Bruce Adams, Applied Materials Ken Kreider, NIST

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I. Temperature Scales, Uncertainty, and Traceability

II. Thermocouples and Thermocouple Wires

Dean Ripple
Thermometry Group
Process Measurements Division
NIST — Gaithersburg, MD

Workshop on
Temperature Measurement
of Semiconductor Wafers
Using Thermocouples

RTP 2000 Conference
September 19, 2000

Outline

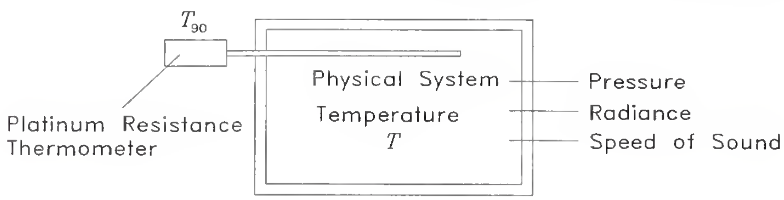
Temperature Scales
Overview of thermocouples (TCs) and reference functions
Traceability
Thermocouple construction types
Laws of thermocouple circuits
Electrical characteristics, differential thermocouples, extension wires, and feedthroughs
Limitations on thermocouple performance
Calibration uncertainties and methods
Calibration of used thermocouples
Resources

What is Thermodynamic Temperature?

Thermodynamic temperature (T) satisfies all of the laws of thermodynamics

Primary Thermometer is an apparatus whose temperature can be calculated from other measured properties (pressure, radiance, speed of sound, etc.).

Examples of Physical Systems: Black body radiation
Speed of sound in ideal gas



Typically, $T - T_{90}$ is measured, where T_{90} = temperature on the International Temperature Scale of 1990 (ITS-90)

What is the International Temperature Scale of 1990 (ITS-90)?

The ITS-90 is an approximation of the thermodynamic temperature scale.

The ITS-90 is a specific recipe for "realizing" temperature, including:
Defined thermometer types
Reproducible fixed points (triple point of water, freezing point of silver, etc.)
The triple point of water is defined as 273.16 K (0 °C = 273.15 K)

Defining instruments relevant to semiconductor thermometry:
Standard Platinum Resistance Thermometer (SPRT) from 13.6 K to 962 °C
Spectral Radiation Thermometer from 962 °C to all higher temperatures

The ITS-90 replaces earlier International Temperature Scales:

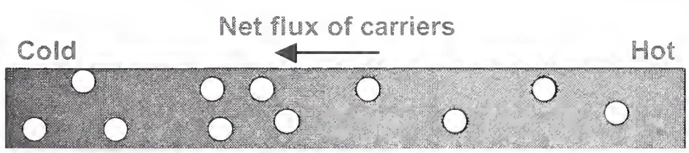
1968	(IPTS-68)
1948	(ITS-48)
1927	(ITS-27)

The IPTS-68 is still in use by some industries

Why use the International Temperature Scale of 1990 (ITS-90)?

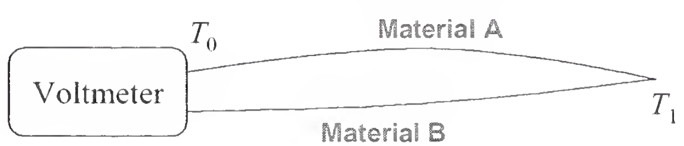
- **The ITS-90 is much easier to realize than true thermodynamic temperature.**
- **The ITS-90 is internationally accepted.**
- **For all present commercial applications, the thermodynamic inconsistency of the ITS-90 is negligible.**
- **Establishment of temperature uncertainty more straightforward on the ITS-90 than with "Process measurement scales".**
- **Consistency of temperature readings worldwide and across applications.**

What is a Thermocouple?



Hotter carriers travel farther before equilibrating with the crystal lattice than cold carriers.

Consequence: charge imbalance when crystal is in thermal gradient.



Net electromotive force = emf = $E = E_A(T_1, T_0) - E_B(T_1, T_0)$

Advantages of Thermocouples

- Cheap
- Wide temperature range (–270 °C to 2100 °C)
- Small (down to 0.25 mm diameter)
- Easy to integrate into automated data systems

Disadvantages of Thermocouples

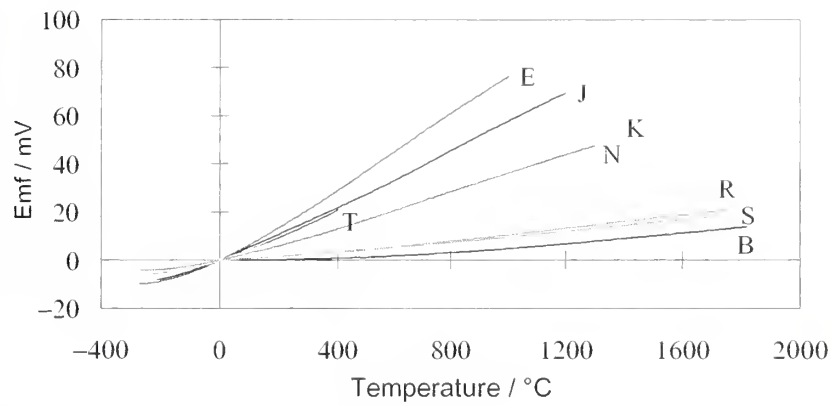
- Small signals, limited temperature resolution (1 mK to 1 K)
- Thermocouple wires must extend from the measurement point to the readout. Signal generated wherever wires pass through a thermal gradient.
- At higher temperatures, thermocouples may undergo chemical and physical changes, leading to loss of calibration.
- Recalibration of certain types of thermocouples or in certain applications is very difficult.

Letter-designated Thermocouple Types

TC type	Ref. func. range, °C	Nominal composition majority component in italics, % in mass Positive leg	Negative leg
B	0 to 1820	*platinum*-30% rhodium	*platinum*-6% rhodium
E	–270 to 1000	*nickel*-chromium alloy	*copper*-nickel alloy
J	–210 to 1200	iron	*copper*-nickel alloy
K	–270 to 1372	*nickel*-chromium alloy	*nickel*-aluminum alloy
N	–270 to 1300	*nickel*-chromium-silicon	*nickel*-silicon-magnesium
R	– 50 to 1768	*platinum*-13% rhodium	platinum
S	–50 to 1768	*platinum*-10% rhodium	platinum
T	–270 to 400	copper	*copper*-nickel alloy

The letter designations define emf versus temperature only — not composition

Emf-Temperature Relationships for the 8 Letter-Designated Thermocouple Types



Notation: E = Emf = Electromotive Force = Thermoelectric Voltage
$S = dE/dT$ = Seebeck Coefficient = Sensitivity

Thermocouple Reference Functions

Sources:

- Reference functions for letter-designated TC types in ASTM E230, IEC 584, NIST Monograph 175
  (ASTM = American Society for Testing and Materials,
  IEC = International Electrotechnical Commission)
- Reference functions for non-letter designated types in: ASTM E1751, E988

Cautions:

- Only a set of spools is guaranteed to match reference function
- Some reference functions are not smooth near 0 °C

Manufacturer develops alloy

↓

Emf versus temperature measured. Reference function fit to data.

↓

Alloy manufactured to match reference function.

Choosing a Thermocouple Type

type E: High Seebeck coefficient, homogeneous materials. Good for low temperatures.
type J: Cheap!
type K: Fairly cheap high temperature thermocouple.
type N: Best base metal thermocouple for high temperatures.
type T: Homogeneous materials. Direct connection of differential pairs to voltmeters.

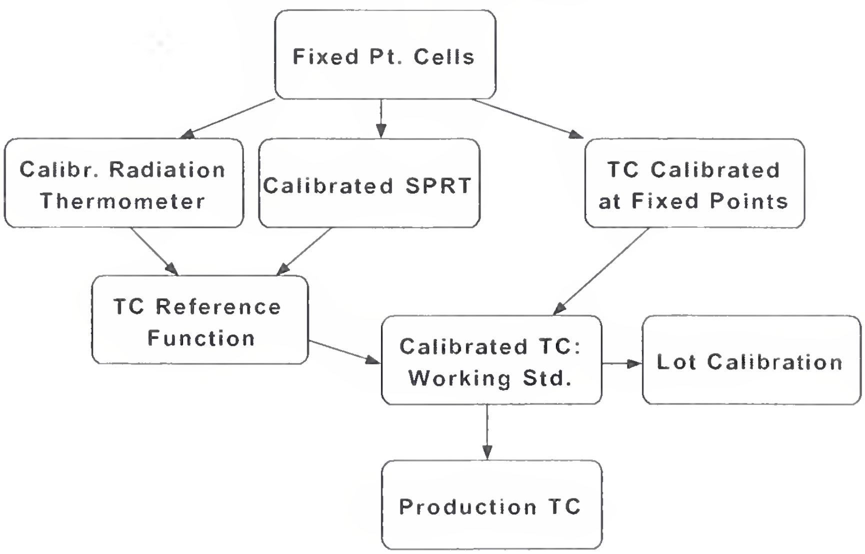
Use type K, E, or T at room temp., type K up to 200 °C, type N in the range 300 °C to 600°C, type N or K above 600 °C

type R, S: Noble metal thermocouple for range 0 °C to1400 °C.
type B: Noble metal thermocouple used from 800 °C to 1700 °C.

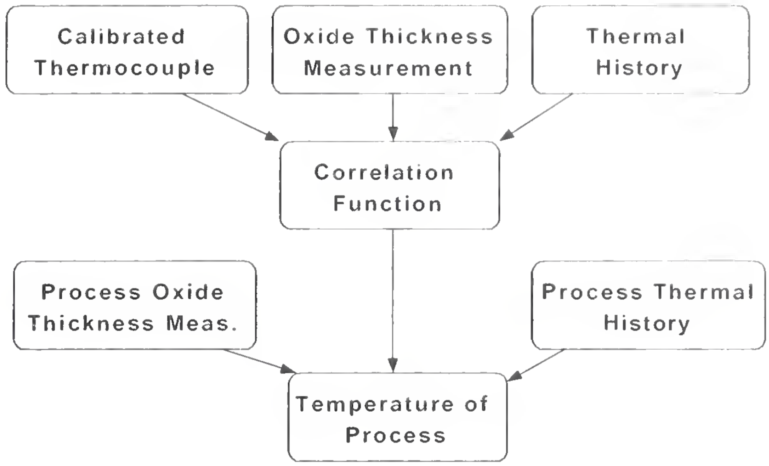
Use type R or S below 1300 °C, type B above 1300 °C.

Platinel: High Seebeck coefficient with some of the stability of types B, R, and S.
Au/Pt: The best accuracy from 0 °C to 1000 °C.
Pt/Pd: The best accuracy from 1000 °C to 1500 °C–not commercial

Traceability on the ITS-90



Traceability using Process Measurements



Traceability depends on the quality and ease of replication of original measurements

Thermocouple Construction Types

Bare wire with ceramic insulators

- the best performance for clean, high temp. environments

Soft-insulated wire

- polymer coatings excellent for use up to 200 °C
- woven ceramic sleeving–not well characterized

Mineral-insulated, metal-sheathed construction (MIMS):

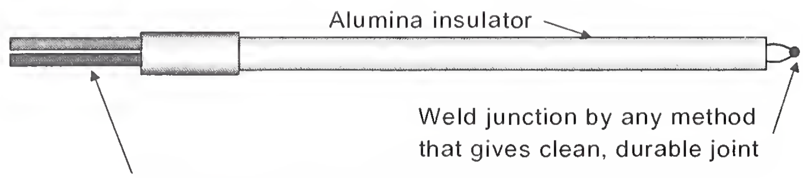
- excellent for base-metal thermocouples at high temperatures
- excellent for unclean environments
- can be bent to shape

Bare wire with ceramic insulators, and outer metal sheath

- not flexible
- better contamination resistance and less mechanical strain than MIMS construction for noble metal thermocouples

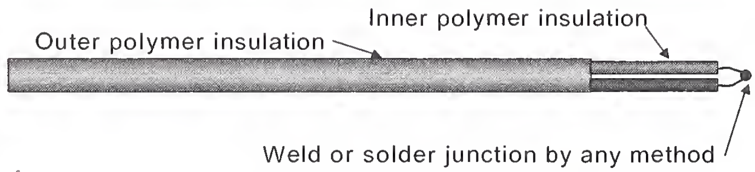
Thin-film thermocouples: discussed by K. Kreider in this Workshop

Bare Wire with Ceramic Insulators



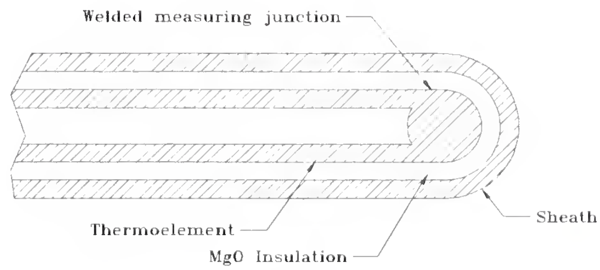
- For noble-metal alloys, use high-purity alumina (99 mass% for typical uses, 99.7 mass% for highest accuracy and stability).
- If old insulators are used, avoid cross contamination. e.g.: Pt wire into a bore that held Pt-Rh, or other base metals into bore that held iron
- Above 1300 °C, alumina insulator itself is a source of impurities.
- Use single, unbroken lengths of ceramic, to prevent contamination and loss of volatile alloy components
- Pt-Rh alloys annealed pre or post assembly for best performance

Soft-Insulated Thermocouples



- Choose polymer insulation based on upper temperature limit
- Woven ceramics are popular in semiconductor applications
  - Always bake out binders to avoid contamination
  - Contamination of thermocouples by ceramic has not been studied well
  - Use single lengths of alumina in high-gradient zone, if possible
  - Contamination is more of an issue with diffusion furnaces than RTP applications (much less time at temperature)

Mineral-Insulated, Metal-Sheathed (MIMS) Thermocouples



- At high temperatures, choice of sheath material is critical
  - for types K and N, sheath material dominates performance
  - for noble metal, Pt-Rh sheaths preferred. Large problems with contamination/strain with non-Pt-Rh sheaths
- MIMS thermocouples are available in small diameters (0.25 mm)
- Sheath protects thermoelements from contamination

Thermocouple Color Codes

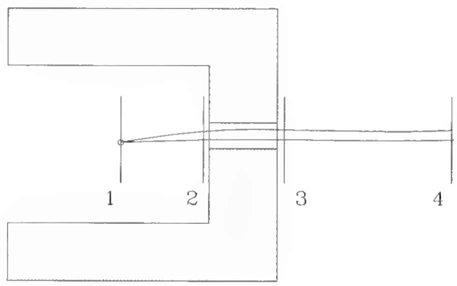
TC Type	IEC Positive Cond., Extension Sheath	ASTM Extension Sheath	ASTM Positive Conductor
B	—	Gray	Gray
E	Violet	Purple	Purple
J	Black	Black	White
K	Green	Yellow	Yellow
N		Orange	Orange
R,S	Orange	Green	Black
T	Brown	Blue	Blue

IEC: Negative Conductor is White for all Types

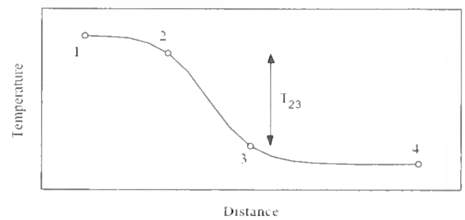
ASTM:

- Negative Conductor is Red for all Types
- For base metal types, duplex insulated thermocouple wire has identical color codes, but with brown overall insulation.

A Key to Understanding Thermocouples...



Thermocouples generate signal primarily in regions of strong thermal gradients. (Region 2-3)



$E_{12} = S_{12}(T_1 - T_2)$	Small
$E_{23} = S_{23}(T_2 - T_3)$	Large
$E_{34} = S_{34}(T_3 - T_4)$	Small

S_{12} = average Seebeck coefficient between points 1 and 2

Fundamental Laws of Thermoelectric Circuits

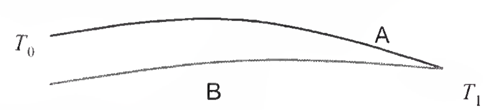
I. EMF OF HOMOGENEOUS WIRE

A homogeneous piece of wire (uniform chemical composition, uniform metallurgical state) will generate no emf if the two ends are at the same temperature, regardless of the temperature between the endpoints.

Example: hook up a copper wire to the inputs of a DVM and immerse the loop into liquid nitrogen. The measured emf will be very small.

A homogeneous piece of wire passing through a thermal gradient will develop an emf, $E(T_0,T_1)$, between its two ends. The emf depends only on the temperature of the end points; cross section is irrelevant.

A pair of wires:



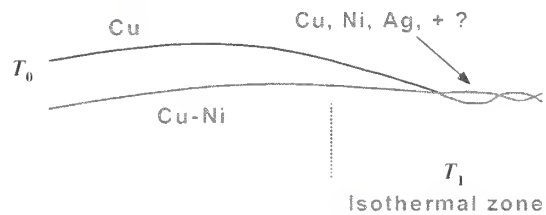
E = emf generated by the loop of wire

$= E_A(T_0,T_1) + E_B(T_1,T_0) = E_A(T_0,T_1) - E_B(T_0,T_1)$

II. EMF OF INHOMOGENEOUS WIRE

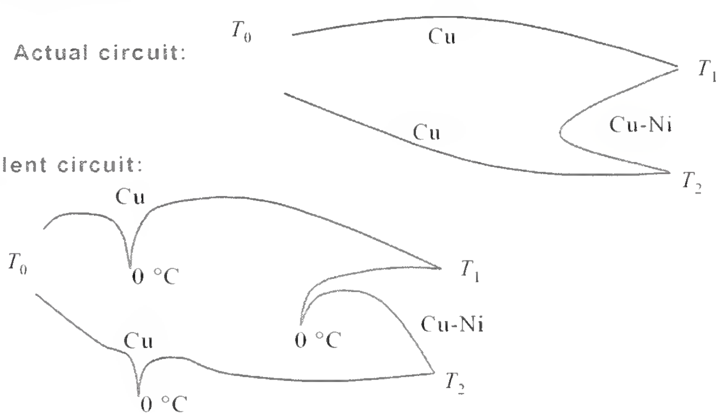
An inhomogeneous piece of wire will generate no emf if the whole piece is at a uniform temperature.

Example: A thermocouple junction is made by brazing, with a silver alloy, a copper and a constantan wire. The junction is placed in an isothermal zone of a furnace. The emf generated by the thermocouple is independent of the composition at the junction because the junction is at a uniform temperature.



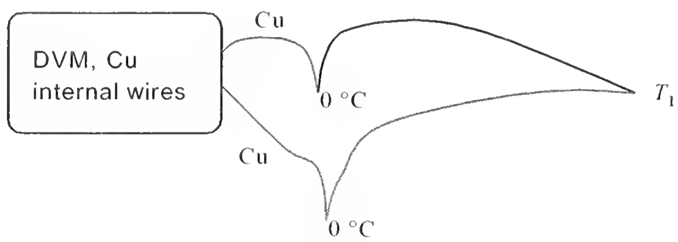
III. EQUIVALENT THERMOCOUPLE CIRCUITS

For thermocouple circuits with reference junctions at a temperature different from 0 °C, an equivalent circuit can be drawn with 0 °C reference junctions. Example: a differential thermocouple pair made of copper/constantan.



Typical thermocouple circuit

Reference junctions maintained at 0 °C by
- immersion into ice bath, made from water/ice slurry
- immersion into thermoelectrically-cooled, sealed ice bath



Reference
junctions at 0 °C

If Reference junctions are not at 0 °C, compensation of emf signal is necessary, by appropriate addition of voltage

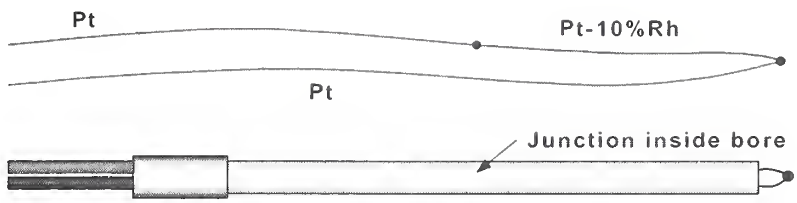
Thermocouple Electrical Characteristics

Electrical characteristics
- low resistance (<100 Ω)
- low DC voltage (<40 mV)

Sources of DC noise
- Extraneous thermal emf (voltmeters, scanner relays, wiring)
- Offset voltages (voltmeters, analog-to-digital converters)
- At high temperatures, electrical leakage through poor insulators

Sources of AC noise
- Magnetic pickup. Use twisted pair leadwire, keep thermoelements close.

Differential Thermocouple Pair



A differential thermocouple pair measures the temperature difference between two points directly

Advantages:

- Very accurate
- Reference junctions must be isothermal, but at any temperature

Disadvantages:

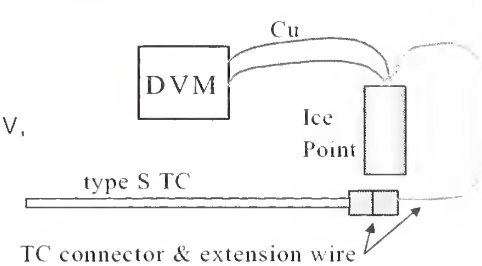
- No measure of absolute temperature at either junction
- Not common commercially

Superior measure of furnace uniformity compared to individual thermocouples in multiple zones

Extension Wires and Cables for Thermocouples

- Extension wires are fabricated from Cu-Ni alloys that are designed to mimic emf response of the standard thermocouple types
- If both ends of the extension wire are within 1 °C, the error in using extension wire is generally negligible
- If there is a large temperature difference between the ends, the error can be dominant
- Emf readings can be corrected, if the temperature difference between the ends remains constant

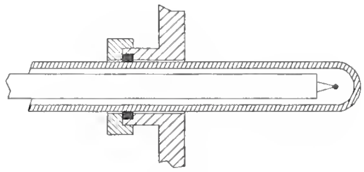
Example: type S extension wire from 0 °C to 23 °C introduces an error of ≈15 μV, equivalent to 1.4 °C for measurement of 900 °C



Hermetic Feedthroughs for Thermocouples

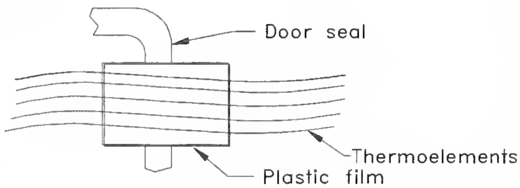
Compression fitting on outer sheath

- Simple
- Poor thermal contact
- Straight insertion only



Thermoelements laminated between adhesive film

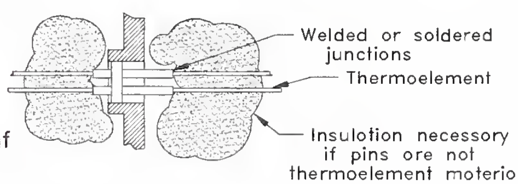
- Simple
- Not truly hermetic
- Wires may kink at door



Hermetic Feedthroughs for Thermocouples

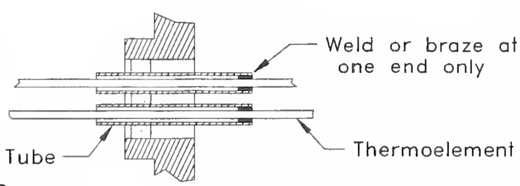
Thermoelements attached to hermetic feedthrough

- No leaks
- Possible extraneous emf
- Difficult to change TC



Thermoelements pass through feedthrough

- No leaks
- Difficult to manufacture
- Solution for unusual TCs



Limitations on Thermocouple Performance

- **Intrinsic variations in alloy composition (small, unavoidable)**
- **Chemical contamination (potentially very large)**
- **Physical strain (moderate: see Bentley in Resources)**
- **Preferential oxidation, volatilization (potentially large)**
- **Hysteresis in structural phase changes (small to moderate, worst for type E and K)**
- **Extension wires, thermocouple connectors, feedthroughs (potentially large, but avoidable)**

Typical variations in indicated *T*, for each effect, $T \approx 900$ ° C

	Base	Noble
small	1 °C	0.1 °C
moderate	3 °C	1 °C
large	≥10 °C	≥ 3 °C

Intrinsic Variations in Thermocouple Homogeneity

There are unavoidable variations in thermoelectric properties along the length of a wire caused by:

- compositional variations in the wire alloy
- variations in the annealing state

In the best circumstances, the fractional uncertainty $\Delta T/T$ of measuring a temperature interval $T_1 - T_2$ is very approximately:

Base metal	10^{-3}
Pt-Rh alloy	10^{-4}
Au/Pt or the best Pt/Pd	10^{-5}

This level of performance requires careful manufacture and use

Chemical Contamination

- Pure elements are more sensitive to impurities than alloys
- In semiconductor processing, absence of oxygen may lead to reduction of oxides and increased levels of free impurities such as Si

Examples of the sensitivity of Pt to impurities

Element	$\Delta E/\mu V$ at 1200 °C per 10^{-6} mass fraction impurity
Cu	0.12
Fe	2.30
Cr	4.04
Mn	0.32
Si	1.17

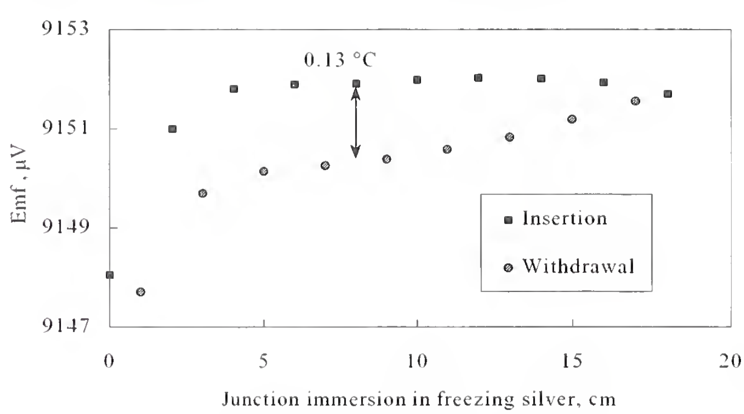
(at 1200 °C, 1 μV equivalent to 0.08 °C for type S)

Cochrane, *Temperature*, Vol. 3, p. 1619 (ISA, 1973)

Preferential Oxidation in Pt-Rh Alloy Thermocouples

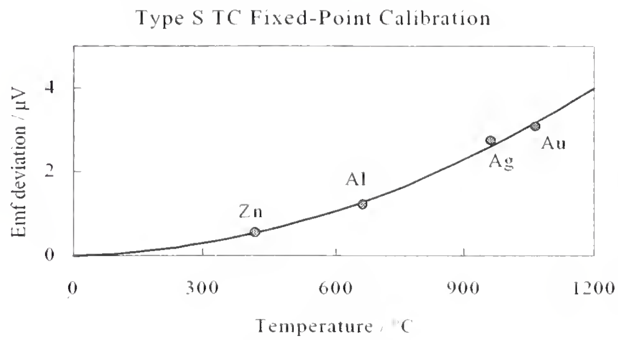
Example: emf of a type S TC at Ag freezing point (961.78 °C) is altered as Rh changes oxidation state during test.

- Effect is 3X larger for some cases of rapid temperature change.
- Effect is reversible, unless oxide is volatile and sublimates

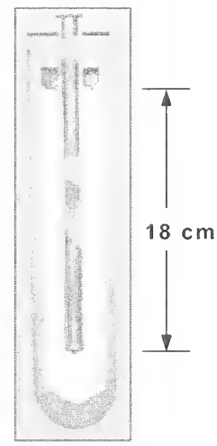


Calibrations in Fixed-point Cells

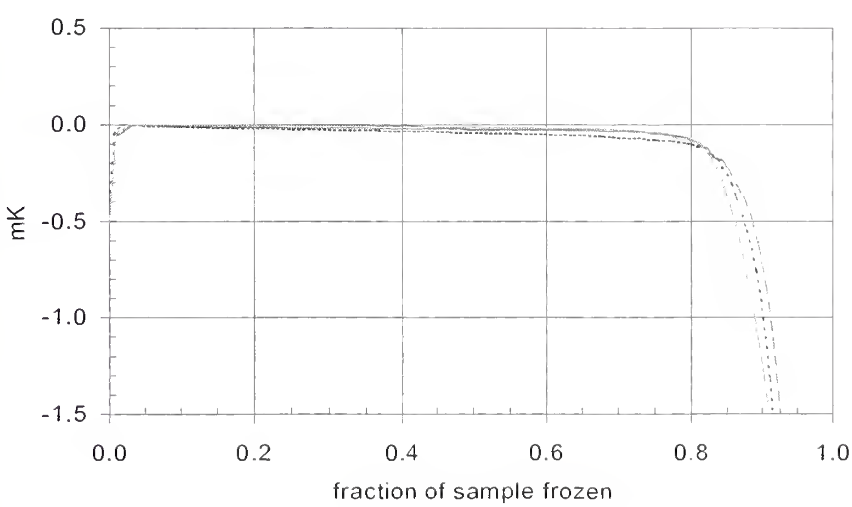
- Fixed point uncertainty <2 mK for Ag and below
- Test uncertainty dominated by stability of test thermocouple



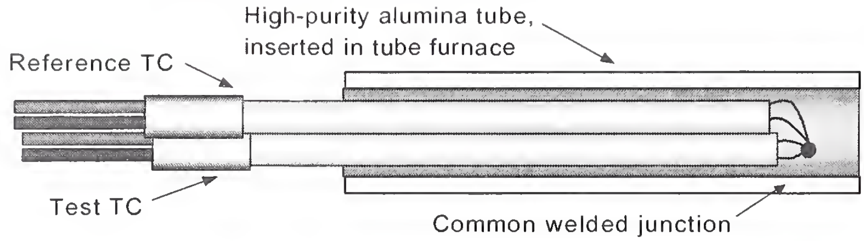
Cross section of a metal freezing-point cell



Example of a Fixed-point: Freezing Curves of an Indium Fixed-point Cell



Comparison Calibrations in Furnaces



- TCs measured simultaneously, to cancel temperature drift
- Measuring junctions at center of furnace to minimize gradients
- Reference TC calibrated at fixed points

NIST Exp. Uncertainties in °C

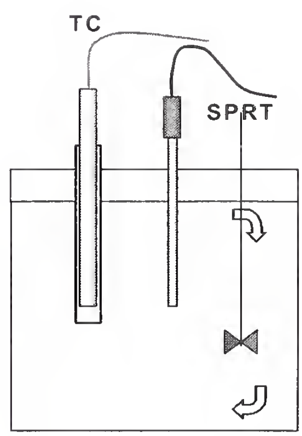
	Base TCs	Noble TCs
0 °C	0.1	0.1
400 °C	0.4	0.2
900 °C	1.0	0.3

Comparison Calibrations in Stirred-liquid Baths

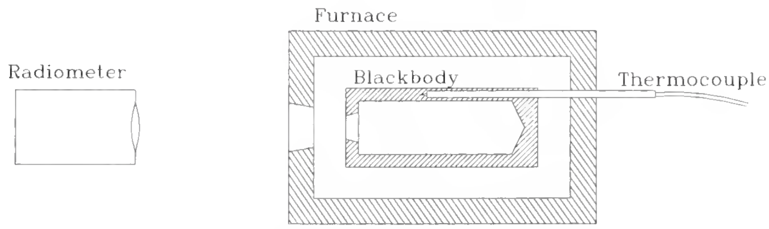
- SPRT expanded uncertainty <1 mK (negligible)
- Bath stability, gradients <20 mK (generally negligible)
- Test uncertainty dominated by stability of test thermocouple

Operating range:

ethanol	−90 °C to 5 °C
water	0.5 °C to 95 °C
oil	95 °C to 275 °C
salt	275 °C to 550 °C



Calibration of Thermocouples above 961.78 °C



Temperatures on the ITS-90 above 961.78 °C defined by radiation thermometry

1. Calibrate radiometer on the ITS-90 at a single fixed-point temperature: silver, gold, or copper.
2. Place thermocouples in or near the blackbody.
3. Measure the emf of the thermocouple while simultaneously measuring the blackbody temperature radiometrically.

Difficult and expensive:
Often only done in determination of reference function

Calibration Uncertainty Components

Temperature reference
- reference calibration uncertainty
- reference stability
- readout uncertainty
- reference junction temperature

Test thermocouple
- test thermocouple stability and homogeneity
- readout uncertainty, including effects of extraneous emf

Thermal equilibrium of test and reference
- Comparison bath/furnace stability
- Comparison bath/furnace uniformity

Method for Evaluation of Uncertainty

ISO Guide to the Expression of Uncertainty in Measurement

1. Evaluate uncertainty components by statistical analysis of data: Type A
   or
   Evaluate by other methods (calculation, calibration cert., etc.): Type B

2. Express all uncertainties at the one standard deviation level.
   Standard uncertainty = u.

3. Combine all uncertainties using the Law of Propagation of Errors, equivalent to root-sum-of-squares (RSS) in simple cases.

4. Expanded uncertainty = $U = ku_c$, where k=coverage factor, often 2.
   If uncertainties are not normally distributed, establish confidence limits for stated k value.

Important point: RSS strongly weights only the few largest uncertainty components. Emphasize careful evaluation of these few components!

Uncertainty Budget for Type S TCs at Fixed Points

Uncertainties in μV	Au (≈1064 °C)	Ag (≈962 °C)	Sb (≈630 °C)	Zn (≈420 °C)
Type B				
Emf Measuring System	0.05	0.04	0.03	0.02
Temperature of Liquidus Point	0.03	0.02	0.08	0.01
Change in Liquidus Point	0.10	0.09	0.06	0.06
Thermocouple Sheath Losses	0.07	0.07	0.06	0.06
Reference Junction Temperature	0.02	0.02	0.02	0.02
Total Type B	**0.14**	**0.12**	**0.12**	**0.09**
Type A				
Uncert. of Check-Standard	0.43	0.35	0.38	0.27
Uncert. of Quadratic Function	0.20	0.20	0.20	0.20
Total Type A	**0.47**	**0.40**	**0.43**	**0.34**
Expanded Uncertainty, $U=2u_c$	**1.0**	**0.8**	**0.9**	**0.7**

Care and Feeding of Thermocouples

Noble Metal Thermocouples:

- Use at the same immersion at which the calibration was performed.
- Protect from contamination by the furnace environment, using single lengths of alumina insulator when possible
- Protect from mechanical strain and kinks

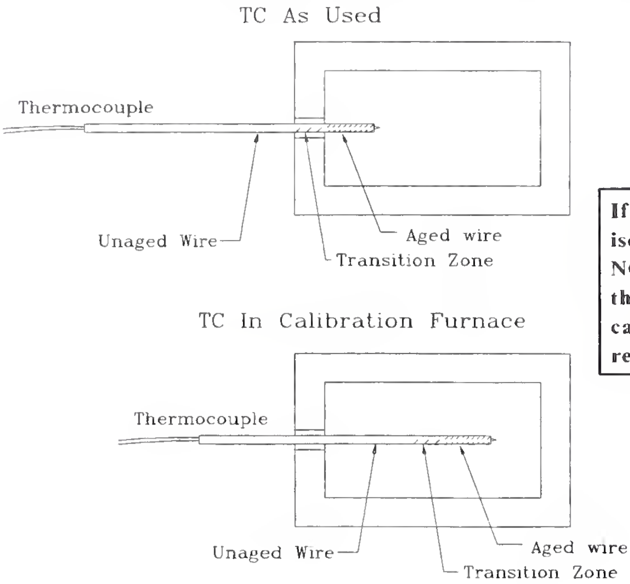
Base Metal Thermocouples:

- Monitor drifts in base metal thermocouples by *in situ* tests
- Protect from contamination using alumina or silica tubes, or use mineral-insulated-metal-sheathed thermocouple wires.
- For each temperature environment to be measured, a new thermocouple should be made, and it should always be used at the same immersion.
- Obey the ASTM upper temperature limits for bare wire thermocouples.

The Difficulty of Recalibrating Used Thermocouples

- With use at elevated temperatures (>200 °C to 400 °C), thermocouples become inhomogeneous.
- Calibration of a used thermocouple in a different apparatus often will produce **meaningless** results! Often, only *in situ* recalibration is meaningful.
- Noble metal thermocouples can be partially restored to a homogeneous state by annealing electrically or in a furnace. Base metal thermocouples are generally not reannealed.
- Any recalibration of a used thermocouple should include a check of the thermocouple homogeneity. (Example: test at different immersions.)

Example of a Misleading Calibration

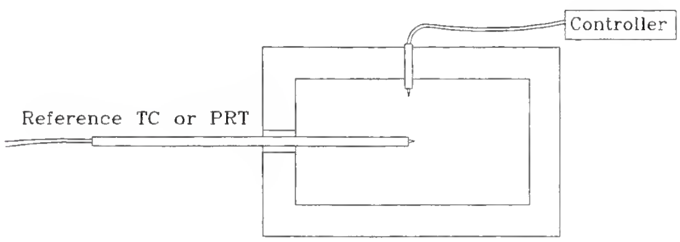


If the furnace is isothermal, there will be NO difference between the original TC calibration and the recalibration.

Alternatives to Recalibration of Used Thermocouples

Option 1. Recalibrate thermocouples *in situ*.

Example: a reference thermocouple is inserted into a furnace with a control thermocouple. The control thermocouple may be recalibrated without removal.

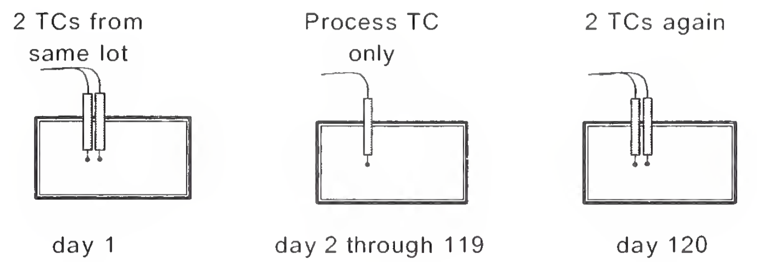


Alternatives to Recalibration of Used Thermocouples

Option 2. Periodic Replacement. Determine a typical drift rate of thermocouples in an application and replace thermocouples periodically.

Drift rate may be determined by:

- Finding similar cases documented in the literature,
- *In situ* calibrations,
- *In situ* comparison measurements between two thermocouples of the same lot, one of which is used and one of which is new.



Resources

Books

- *Traceable Temperatures*, J. V. Nicholas and D. R. White (John Wiley, 1994)
- *The Theory and Practice of Thermoelectric Thermometry*, Vol. 3 of the *Handbook of Temperature Measurement*, R. Bentley (Springer, 1998)
- *Manual on the Use of Thermocouples*, ASTM, MNL-12 (ASTM, 1993)

Links

- ASTM standards and tables: www.astm.org
- NIST Thermometry Group : www.cstl.nist.gov/div836/836.05/home.htm
- General reference on thermometry: www.temperatures.com

Training

NIST Precision Thermometry Workshop, every March and October. Contact Andrea Swiger at andrea.swiger@nist.gov.

NIST

SURFACE TEMPERATURE MEASUREMENTS

- KEN KREIDER
- THERMOMETRY GROUP, NIST
  - OCTOBER 20, 2000

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Surface Temperature Measurements in Engineering

- PRODUCTION
  - hot rolling, forging, glass forming, plastic molding
  - RTP of silicon wafers
- TEST AND EVALUATION
  - gas turbine engines, diesel engines
  - calibration of pyrometers
- APPLICATION AND OPERATION
  - bearing surfaces, boiler tubes
  - control

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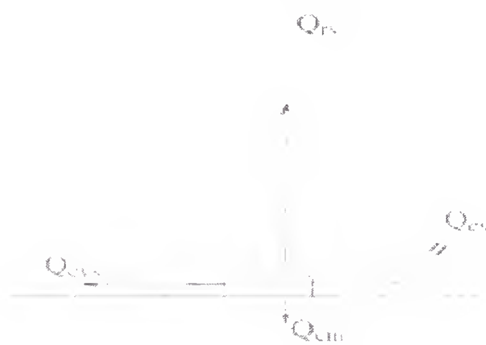
Heat Transfer near Surface Temperature Sensor



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HEAT TRANSFER FROM SURFACES

- $Q_c = kA\ dT / ds$
- $Q_{CV} = h_C A \Delta T$ $\quad hc = f(s, \angle)$
- $Q_{rad} = (F \epsilon A)(T_s^4 - T_b^4)$ $\quad \epsilon = f(x_{ox}, \delta_{rms}, \lambda)$

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INSTALLATION TYPES

- PERMANENT
  - **DIRECT**
  - **HEAT COLLECTING PAD**
  - **GROOVED**
- PROBES
  - **UNGROUNDED**
  - **GROUNDED**
  - **EXPOSED**
  - **BUTTON**

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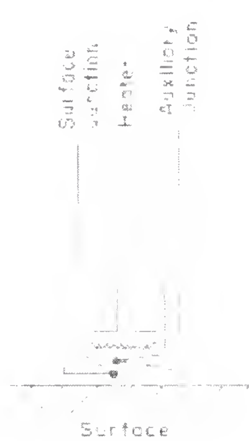
Thermocouple Probe with Auxiliary Heater



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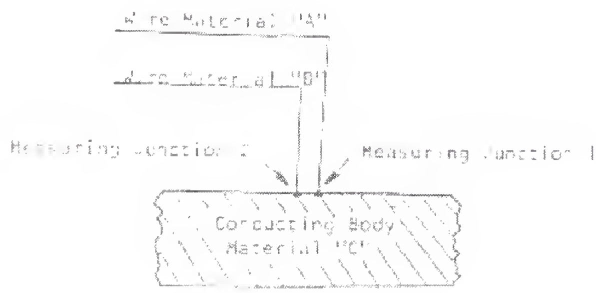
Separated Thermocouple Junction



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SEPARATED JUNCTION

- $e_o = e_m + (S_1 - S_2)(T_1 - T_2) / 2$
  - T_1 and T_2 = junction temperatures
  - e_o = measured output
  - e_m = output if $T_1 = T_2$
  - S_1, S_2 = Seebeck coefficient of material C versus materials A and B, and Seebeck coefficient of thermocouple wires A and B

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SOURCES OF ERROR

- PERTURBATION ERROR
  - **EMISSIVITY**
  - **CONDUCTION**
  - **INSULATION**
  - **CONVECTION**
- DISPLACEMENT ERRORS
  - **OFFSET VS GRADIENT**
  - **DISSIMILARITY OF MATERIALS**
- TRANSIENT RESPONSE
  - **MASS CHANGE**
  - **HEAT TRANSFER RATES**

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PROCEDURES FOR MINIMIZING ERROR

- **USE SMALLEST POSSIBLE INSTALLATION**
- **USE ISOTHERM FOR TC WIRES FOR >20 D**
- **LOCATE JUNCTION AT SURFACE**
- **MINIMIZE CHANGES IN CONVECTIVE AND RADIATIVE HEAT TRANSFER**
- **MINIMIZE TRANSIENT LAG**
- **MINIMIZE THERMAL RESISTANCE FROM SURFACE TO JUNCTION**

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THIN-FILM THERMOCOUPLES

- SMALL SIZE
  - FAST RESOLUTION (< 1µs)
  - FINE SPATIAL RESOLUTION (0.1 mm)
- LOW COST
  - AUTOMATED PRODUCTION
  - LOW MATERIALS COST
- COMPATIBLE WITH IC PRODUCTION
  - MATERIALS COMPATIBILITY
  - SAME FABRICATION TECHNOLOGY
- VOLTAGE OUTPUT
  - SIMPLE INSTRUMENTATION-NO POWER REQUIREMENTS

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APPLICATIONS

- GAS TURBINE BLADES AND VANES
- DIESEL ENGINE CYLINDER WALLS
- THERMAL CONVERTORS
- BEARINGS AND SEALS
- ELECTRONIC PACKAGE THERMAL MONITORS
- HEAT FLUX GAGES
- THERMOPILES
- CALIBRATION TOOLS FOR RADIOMETRIC MEASUREMENTS

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LOW HEAT REJECTION DIESEL ENGINE ISSUES

- IN CYLINDER CONVECTIVE AND REDIATIVE HEAT TRANSFER
- CYCLIC TRANSIENT HEAT TRANSFER IN LAYERS NEXT TO COMBUSTION CHAMBER
- HEAT TRANSFER: PISTON / RING / LINER
- STEADY STATE HEAT TRANSFER
- TRANSIENTS IN WARM UP AND POWER CHANGES

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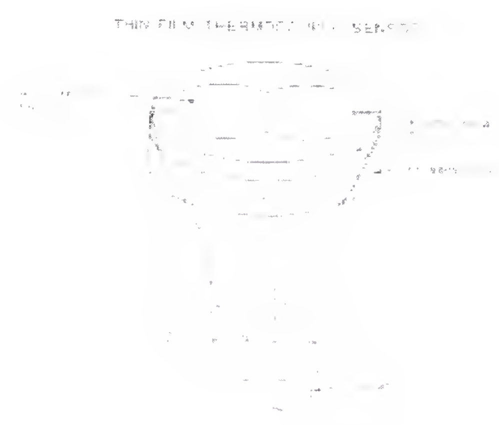
Diesel Engine Sensor Plug



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Heat Flux vs Crank Angle in Diesel Engine

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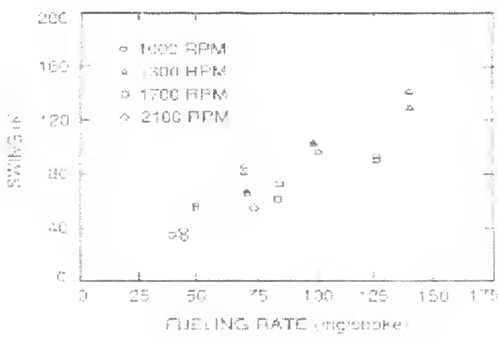
Swing Temperature Measured with Thin-film Thermocouple in Diesel Engine Cylinder



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THIN-FILM THERMOCOUPLE TRANSIENT THERMAL RESPONSE

- TFTC JUNCTION ON SUBSTRATE (ZrO_2, $Al_2O_{3,}$, etc.)
- EXIMER LASER (ns) ON 1 mm^2 JUNCTION
- TRACK ON CR OSCILLOSCOPE
- DETERMINE THERMAL CONDUCTIVITY AND DIFFUSIVITY OF SUBSTRATE MATERIAL

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Thin-film Thermocouple Time Response on Aluminum Oxide

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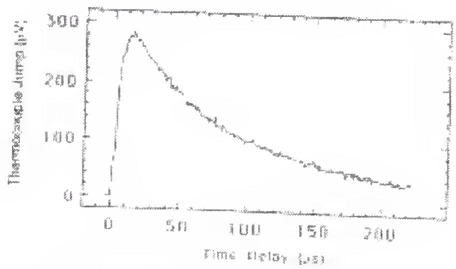
Thin-film Thermocouple Time Response ZrO_2



Transient thermal response of a [illegible] µm thick Pt/Au thermocouple on plasma sprayed zirconia. Sensitivity of [illegible] µV/K. Characteristic time (decay) of 60-80 µs. The rise time of 5-10 µs is limited by the bandwidth of the amplifier.

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RAPID THERMAL PROCESSING

ADVANTAGES

COMPATIBILITY WITH CLUSTER TOOLS

FABRICATION CYCLE TIME

PROCESS REPEATABILITY

REDUCED FOOTPRINT

REQUIREMENTS

WAFER TEMPERATURE UNIFORMITY

ABSOLUTE TEMPERATURE CONTROL

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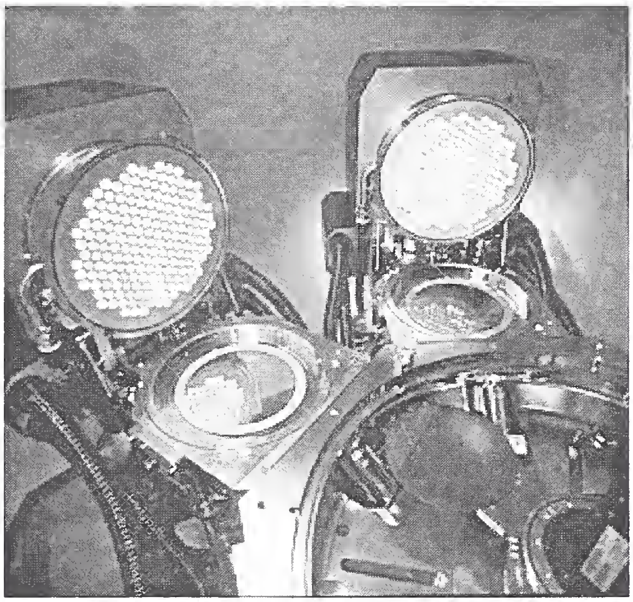

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THIN-FILM VERSUS WIRE THERMOCOUPLES

	thin-film		wire
junction volume	$2x10^{-5}$	mm^3	10^{-2}
profile	10^{-3}	mm	0.5
attachment	$2x10^{-7}$	mm^3	1
ΔT_{900}	< 1 °C		3-6 °C

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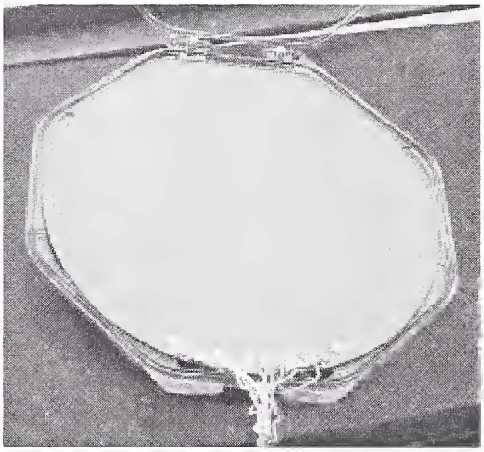
Calibration Wafer with Wire/Thin-film thermocouples



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WAFER SURFACE TEMPERATURE MEASUREMENT

UNCERTAINTY $k = 1$

- **Pt/Pd wire thermocouple** $u_c = 1$ °C
- **S for thin-film thermocouple** $u_c = 3$ % x 10 °C

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Relationship between Thermocouple and Radiation Thermometer Measurements

D.P. DeWitt
Optical Temperature and Source Group
Optical Technology Division, PL
NIST – Gaithersburg, MD

Workshop on
Temperature Measurement
of Semiconductor Wafers
Using Thermocouples

RTP 2000 Conference
September 19, 2000

OPTICAL TECHNOLOGY DIVISION

1

Overview

Objectives: fundamentals of RTs, model-corrected measurements, LPRT calibration, comparison of RT & TC; about good practice

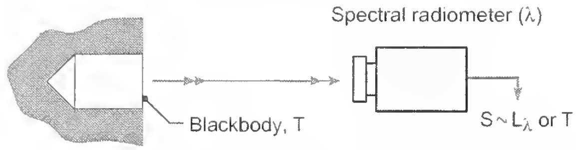
1. The Measurement Problem: getting T_{rad} from T_λ
   - Blackbody calibration, measurement equation
   - Model-corrected RT measurements, T_{rad}
2. Radiation Modeling: three idealized reactor cases
3. Light-Pipe RTs
   - Calibration against blackbodies, uncertainties
   - Characterization for use in RTP environment
4. NIST Test Bed Experiments: comparing T_{tc} and T_{rad}
5. Recommendations for Good Practice using RTs
6. References and Bibliography

OPTICAL TECHNOLOGY DIVISION

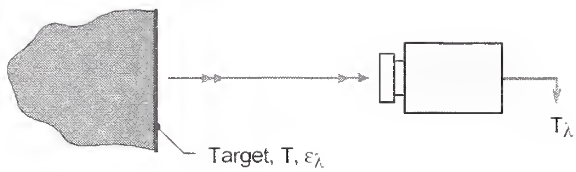
2

1. The Measurement Problem

- **Radiation thermometer, RT - a radiometer calibrated to indicate temperature of a blackbody, T.**



- **Spectral radiance temperature, T_λ – indicated temperature when viewing a real target experiencing irradiation from the surroundings.**



OPTICAL TECHNOLOGY DIVISION

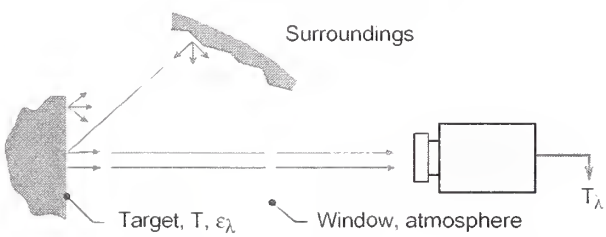
[Reference 1, 2]

3

1. The Measurement Problem – TME

- **Temperature measurement equation, TME – relates T_λ to T.**

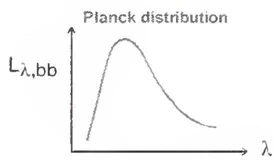
$$L_\lambda(\lambda, T_\lambda) = \varepsilon_\lambda L_{\lambda,bb}(\lambda, T) + (\ldots\text{reflected irradiation}\ldots)$$



L_λ - spectral radiance, W/(m²-μm-sr)

$L_{\lambda,bb}(\lambda, T) = c_1\lambda^{-5}\,[\exp(c_2/(\lambda T)) - 1]^{-1}$

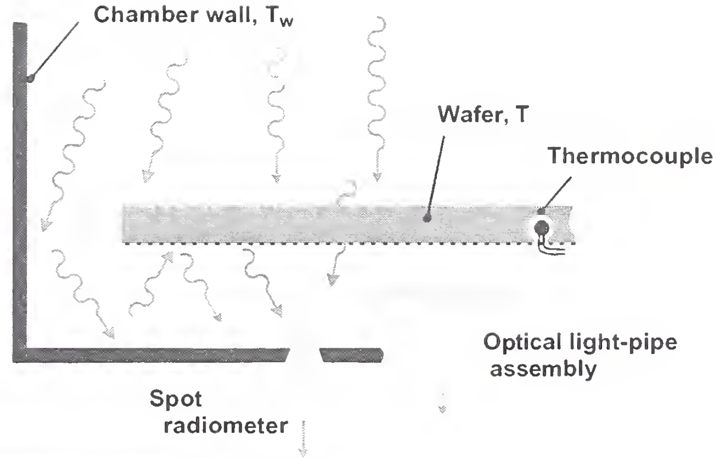
ε_λ - spectral emissivity



OPTICAL TECHNOLOGY DIVISION

4

The Radiation Environment



OPTICAL TECHNOLOGY DIVISION

5

1. The Measurement Problem – Methodology

- Characterizing the Radiation Environment: specifying the irradiation due to emission, reflection, stray radiation.
- Thermal Modeling: predicting the spectral radiance exitent from target reaching RT in terms of wafer properties and radiation environment; three limiting cases to explore.
  - Freely radiating
  - Cold reflective walls
  - Hot emitting walls
- Model-Corrected RT Measurements: using the TME with thermal radiation model(s) to determine wafer temperature and uncertainty of the measurement.
- Calibrating RT with a TC Measurement: for conditions of the calibration, $T_\lambda = T_{tc}$; for other conditions, require the TME.

OPTICAL TECHNOLOGY DIVISION

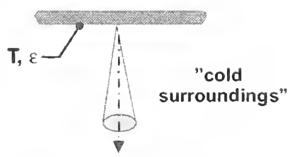
6

2. Radiation Modeling: TMEs, idealized reactors

- **Radiation thermometer, RT - a radiometer calibrated to indicate temperature of a blackbody, T. For other conditions or targets, indicates spectral radiance temperature, T_λ.**

- **Freely radiating target – cold surroundings; T_λ**

$$\frac{1}{T} = \frac{1}{T_\lambda} + \frac{\lambda_e}{c_2} \ln(\varepsilon_\lambda)$$



c_2 = 14,388 μm-K, second radiation constant
λ_{eff} = 0.95 μm, RT effective wavelength

$$L_\lambda(\lambda, T_\lambda) = \varepsilon_\lambda L_{\lambda,b}(\lambda, T)$$

Case: T = 1000 K = 727 °C, ε = 0.67, find $T - T_\lambda$ = 29 K

OPTICAL TECHNOLOGY DIVISION

[Reference 3]

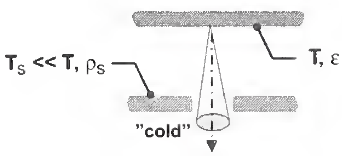
7

2. Radiation Modeling – TMEs, idealized reactors

- **Cold, reflective wall (shield), T_λ**

$$\frac{1}{T} = \frac{1}{T_\lambda} + \frac{\lambda_e}{c_2} \ln(\varepsilon_{eff})$$

$$\varepsilon_{eff} = \frac{\varepsilon}{1 - (1-\varepsilon)\rho_s}$$

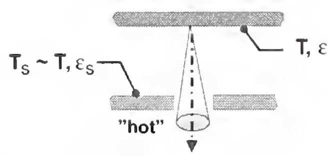


Case: T = 1000 K = 727 °C, ρ_s = 0.99, ε = 0.67, find

ε_{eff} = 0.995 $T - T_\lambda$ = 0.3 K

- **Hot, black wall (shield), T_λ**

$$L_{\lambda,b}(T_\lambda) = \left[1 - \frac{1/\varepsilon - 1}{1/\varepsilon + 1/\varepsilon_s - 1}\left(1 - \frac{L_{\lambda,b}(T_s)}{L_{\lambda,b}(T)}\right)\right] L_{\lambda,b}(T)$$

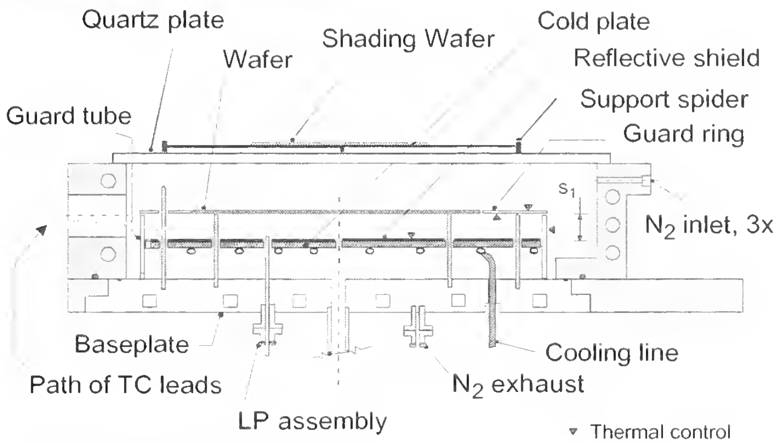


Case: T = 1000 K, ε = 0.67; T_s = 990 K, ε_s = 0.95 find $T - T_\lambda$ = 3 K

OPTICAL TECHNOLOGY DIVISION

8

2. Radiation Modeling – NIST Test Bed



NIST RTP Test Bed

OPTICAL TECHNOLOGY DIVISION

[Reference 4]

9

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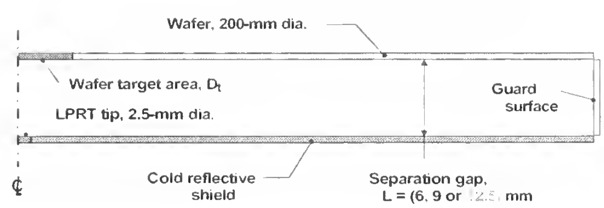
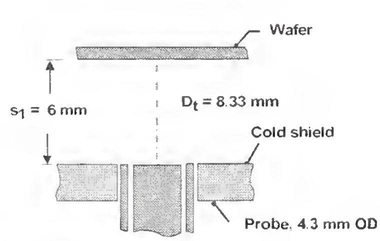
2. Radiation Modeling – NIST Test Bed

Five-Region, 24-Zone Enclosure Model



Target - LPRT Configuration



Model Assumptions:

1. Uniform radiosity on surfaces
2. Diffuse or specular shield
3. Prescribed uniform temperatures for wafer, guard, edge ....
4. Target diameter, D_t, function of gap distance
5. Wafer effective emissivity, $\varepsilon_{eff} = J_t / E_{bt}$

OPTICAL TECHNOLOGY DIVISION

[Reference 3]

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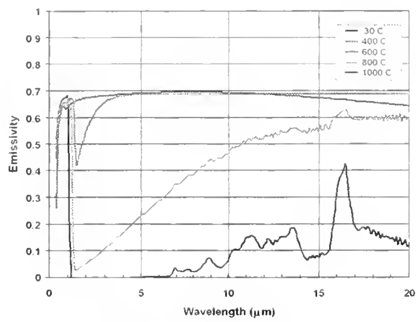
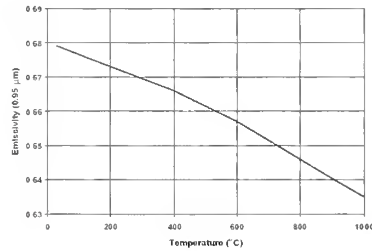
2. Radiation Modeling – NIST Test Bed

Silicon spectral emissivity (with thermal oxide)





OPTICAL TECHNOLOGY DIVISION

[Reference 5]

11

3. Light-Pipe Radiation Thermometers Technology Issues

Calibration of LPRTs against NIST Blackbody

- Remarkable discrepancies in factory calibrations
- Differences between hot and cold LPs

Thermal Characterization

- Calibration vs. application conditions (hot - cold)
- LP tip - wafer interaction, temperature disturbance

Spatial Characterization

- Thermal effects on field-of-view (FOV)
- Benchmarking FOV effects

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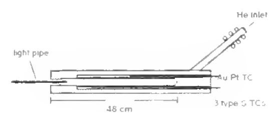
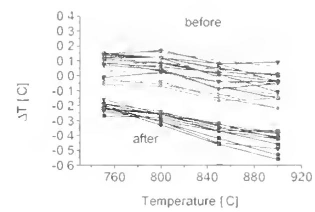
The NIST Sodium Heat-Pipe Blackbody (Na-HPBB)



LPRT calibration shifts (1 yr)

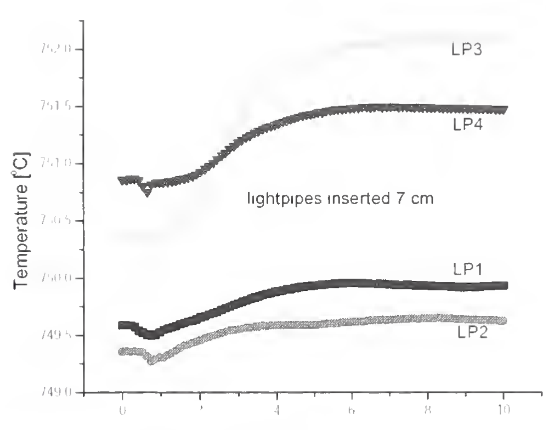


Uncertainties in LPRT Calibrations

Factor	*u (K)*
BB radial uniformity	0.29
BB length uniformity	0.10
LPRT noise	0.01
LPRT short-term drift	0.03
Total (k=1)	0.30

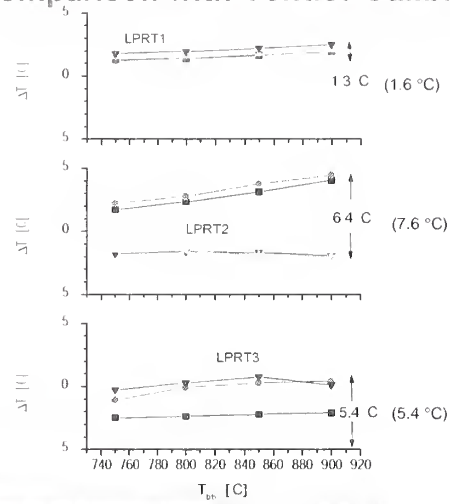
[Reference 6,7]

Hot vs. Cold Light-Pipe RT Calibration



3. Light-Pipe RTs - Calibration

Comparison with Vendor Calibrations



- Four-channel LPRTs
- Three vendors
- NIST Na-HPBB reference
- LP conditions
  - cold vs. (hot)

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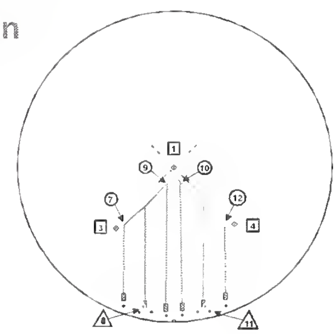
[Reference 7]

15

4. NIST Test Bed Experiments – Objectives

Development and demonstration of thin-film/wire thermocouple (TFWTC) Test Wafer



In-situ calibration of LPRT using Test Wafer

Comparison of temperature measurements by TFTC and Model-Corrected LPRT

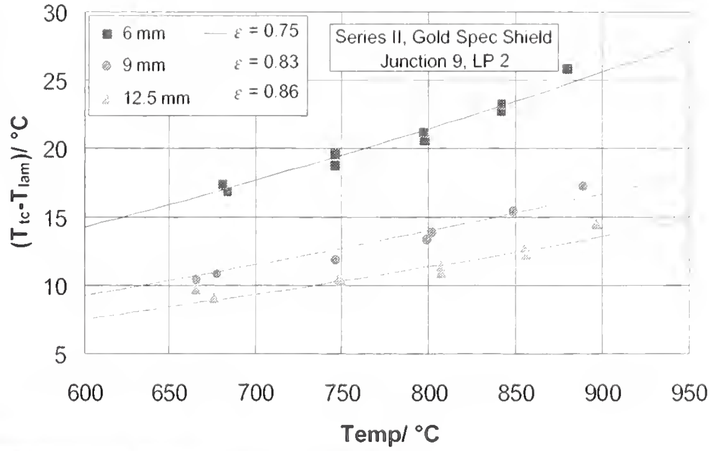
OPTICAL TECHNOLOGY DIVISION

[Reference 4]

16

LPRT Measurements

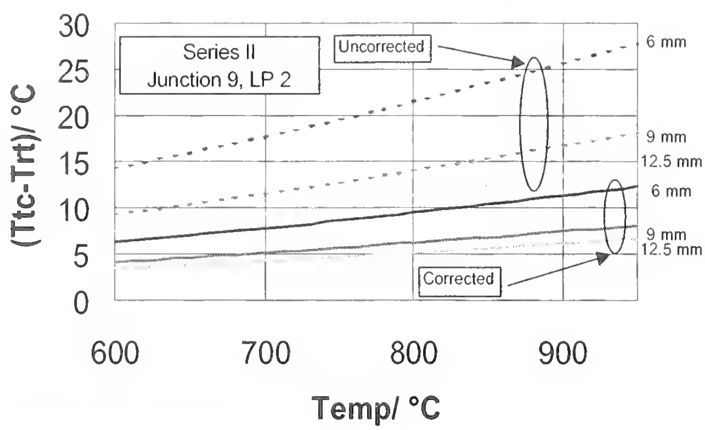
(Series II with best fit emissivity)



In Situ Calibration of LPRTs Temperature Uncertainties (k = 1)

Component	u_c(°C)
TFWTC calibrations (10 °C)	0.3
TC emf measurements	0.1
LPRT measurements	0.1
Wafer temperature fluctuations	0.4
Wafer temperature drift	0.1
Junction/target temp difference	2.0
Total	2.1

Model-corrected LPRT Measurements



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[Reference 3]

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Comparison of TFWTC and LPRT Measurements Temperature Uncertainties (°C, k = 1)

LPRT		TFTC	
Calibration	**0.2**	**TFTC (10 °C)**	**0.3**
Effective emissivity	**3.0**	**Pd/Pt TC**	**0.1**
Junction/target temperature difference	**2.0**	**TC emf**	**0.1**
Temperature fluctuations	**0.4**		
Temperature drift	**0.1**		
LPRT display	**0.1**		
Subtotal	3.5	Subtotal	0.3

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4. NIST Test Bed Experiments

Summary – Calibrating Against TC

- NIST Test Wafer
- Benchmark calibrations of TFWTC and LPRT

Calibration	u(°C)
TFWTC (10 °C)	0.3
LPRT	0.2

- Test Bed measurement (present) uncertainties

NIST TFWTC technology	0.3 °C
In-situ LPRT calibration	2.1 °C
Model corrected, blackbody calibrated LPRT	3.5 °C

- Thermal modeling for effective emissivity
  - Transferring calibrations to applications
  - Establishing uncertainties

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[Reference 9]

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5. Recommendations for Good Practice

(1) Calibrate the RT under same conditions as application.

- LP used hot or cold; temperature gradient
- Characterize blackbody for gradients
- Identify traceability artifact

(2) Characterize the radiation environment.

- Formulate the Temperature Measurement Equation (TME)
- Emissivity of wafer – bare, oxide, ...roughness
- Surroundings of wafer – hot/cold walls hot, shields, stray light
- Sensor placement – interaction with wafer, operating temperature

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5 Recommendations for Good Practice – Cont'd

(3) Make model-corrected measurements, establish uncertainties.

- RT calibrated against blackbody; limits of uncertainties known
- Develop radiation model of the characterized radiation environment
- Seek first-order models based upon geometries amenable to analysis
- Establish realistic, first-cut uncertainty estimates
- Identify largest contributing factors to uncertainty
- Design and perform experiments to validate model(s), and hence establish confidence in uncertainty estimates

(4) Use *in-situ* calibration with TC to establish reliability of RT measurements.

- Characterize RT under blackbody conditions to assure proper operation
- Establish limits of error to traceable TC artifact
- Identify the conditions under which the in-situ calibration is performed
- Establish limitations of calibration – emissivity variability, chamber conditions

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6. References

[1] DeWitt, D.P. and G.D. Nutter (Eds.), Theory and Practice of Radiation Thermometry, Wiley Interscience, 1988.

[2] Short Course, *Temperature Measurement by Radiation Thermometry*, Optical Technology Division. NIST, http://physics.nist.gov.Divisions/Div844/rtsc.html

[3] Tsai, B.K. and D.P. DeWitt, "ITS-90 Calibration of Radiometers Using Wire/Thin Film Thermocouples in the NIST RTP Tool: Effective Emissivity Modeling," *Proc. of 7th Intl. Conf. on Adv. Thermal Processing of Semiconductors*, RTP'1999, (H. Kitayama, et al., eds), p 125, 1999

[4] Meyer, C.W., et al , "ITS-90 Calibration of Radiometers Using Wire/Thin Film Thermocouples in the NIST RTP Tool: Experimental Procedures and Results," *Proc. of 7th Intl. Conf. on Adv. Thermal Processing of Semiconductors*, RTP'1999, (H. Kitayama, et al., eds), p 136, 1999.

[5] *Multi-RAD*, PC software, optical and radiative properties of semiconductor materials, Private communication, Dr. J.E. Hebb, Eaton Corp., Sept 15, 1997.

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[6] Lovas, F.J., B.K. Tsai, and C.E. Gibson, "Meeting RTP Temperature Accuracy Requirements: Measurement and Calibrations at NIST," *Mat. Res. Soc. Symp. Proc.*, v 525, p 127, 1998.

[7] Tsai, B.K., C.W. Meyer and F.J. Lovas, "Characterization of Light-Pipe Radiation Thermometers for the NIST Test Bed," *Proc. of 8th Intl. Conf. on Adv. Thermal Processing of Semiconductors*, RTP'2000, (B. Lojek, et al., eds), September 2000.

[8] Kreider, K.G., et al., "Calibration of Light-pipe Radiation Thermometers in an RTP Tool at 1000 °C", to be

[9] Kreider, K.G., et al., "Calibration of Light-pipe Radiation Thermometers in an RTP Tool at 1000 °C", to be published in *Proc. of 8th Intl. Conf. on Adv. Thermal Processing of Semiconductors*, RTP'2000, (B. Lojek, et al., eds), September 2000.

TOTAL SOLUTIONS

RTA T/C and RT Measurements

B. E. Adams

Applied Materials, Santa Clara, CA

Workshop on Temperature Measurement of Semiconductor Wafers Using Thermocouples

RTP 2000 Conference
September 19, 2000

1

APPLIED MATERIALS

OVERVIEW

1. RTP Hardware
   The Measurement Environment
2. Temperature Measurement Problems
   In-Situ Scales
   Ripple
   Emissometer
3. Lightpipe Pyrometer Calibration
   Hot Calibration Issues
   Cold Calibration Issues
4. Why Traceability?
   Cost
   Portability
5. Bridging to ITS-90 - modeling wafer, chamber, pyrometer interactions
6. Recommendations
7. References and Bibliography

2

APPLIED MATERIALS

RTP Hardware

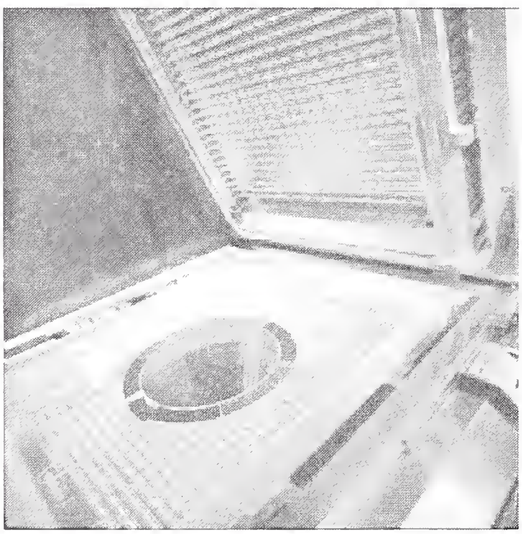
- **Variations**
  - Cold wall / hot wall
  - wafer rotating or stationary
  - single arc lamp, linear lamps, concentric lamp arrays
  - single sided or dual sided heating

- **Generic features**
  - non thermal equilibrium conditions
  - non contaminating environment
  - single wafer processing

3

APPLIED MATERIALS

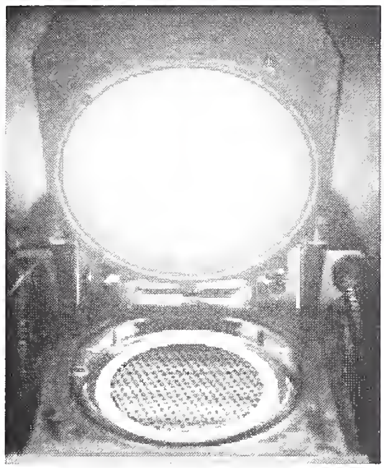
Linear Lamps, Dual Sided Heating, Rotating Wafer STEAG 3000 RTP System



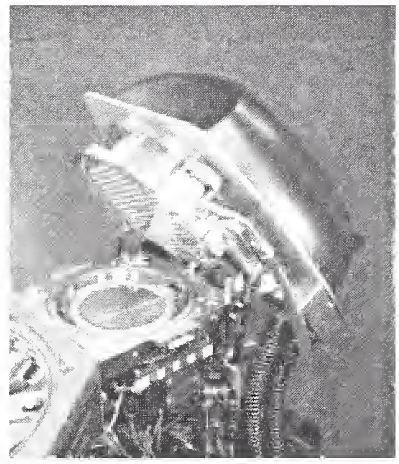
4

APPLIED MATERIALS

Concentric Lamps, Single Sided Heating, Rotating Wafer
Applied Materials



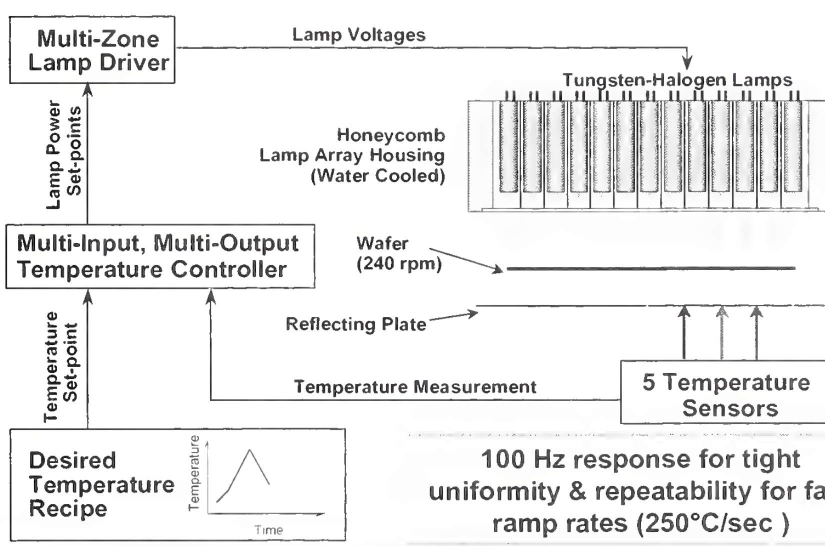
200mm Radiance



300mm Radiance

5

Radiance Centura Temperature Control System
High speed, Closed-Loop, Real-time, Multi-point Control

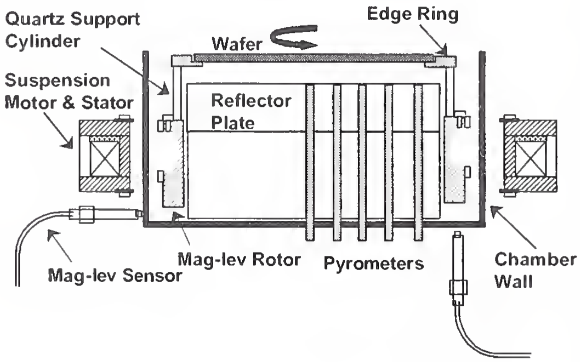


100 Hz response for tight uniformity & repeatability for fast ramp rates (250°C/sec)

6

Radiance Centura
Magnetically-Levitated Wafer Rotation

Mag-lev Suspension:
- Rotation is closed-loop controlled
- Rotor support cylinder, edge ring and wafer
- Backup power brings rotor to gentle halt
- Rotor does not contact any chamber parts while in motion
- Fast acceleration & deceleration



Magnetic-levitation offers clean and fast wafer rotation for improved process results & easier serviceability

Thermocouple Calibrations

- T/C - Great under isothermal conditions
- Calibrations get very complex with temperature gradients
  - Radiative coupling differs for thermocouples and silicon
  - Spectral issues (wafer transparent, t/c opaque for 50% of the energy spectrum)
  - Heat conduction to or from the leads
  - Thermal isolation from the wafer by the binders
- **Net result is that traditional T/C wafers are limited in accuracy (5 °C)**

Historical Problems of RTP Temperature Measurement

- Variability of wafer optical properties
  - wavelength
  - temperature
  - view angle
  - film stack
  - film thickness
  - dopants
  - roughness
- Lamp Radiation
- Wafer rotation and contamination issues
- Emphasis on REPEATABILITY and CONTROL

9

APPLIED MATERIALS®

Temperature Error for a 10% Uncertainty in Emissivity

	Measurement Wavelength μm				
Temp °C	0.95	1.7	2.4	3.4	5
300	2	4	5	8	11
500	4	7	10	14	21
700	6	11	16	22	33
900	9	16	23	33	48
1100	12	22	31	45	66

10

APPLIED MATERIALS®

Process Temperature Scales

- RTO 1100 °C, 60 sec, yields 0.828+/-0.015 A/ °C
- RTA 1050 °C, 20 sec, As 1E16 40KeV, w/ 10% O_2, yields -0.35 Ohms/Sq/ °C
- We use these virtually every day all over the world

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Process Temperature Scale Repeatability

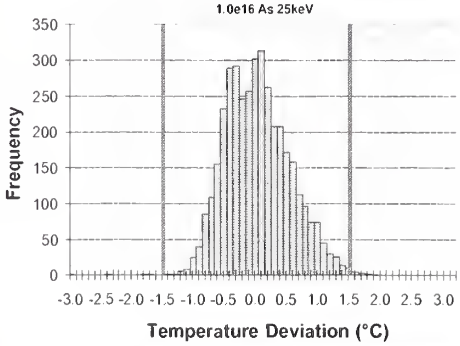
300mm Radiance RTA/RTO Performance

5 Days 3500 Wafers Run 121pt Contours 3mm EE

RTA Temperature Histogram

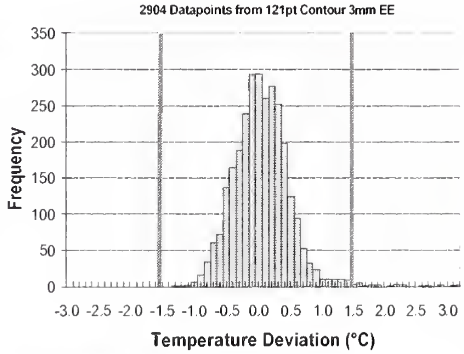
3872 Datapoints from 121pt Contour 3mm EE

1.0e16 As 25keV



RTO Temperature Histogram

2904 Datapoints from 121pt Contour 3mm EE



Temperature Control Performance

Repeatability and Within Wafer Results < 1.5°C 3σ

12

Process Temperature Pros and Cons

- Advantages
  - **industry standard -** *Historically Repeatability has been more important to the processing industry than Accuracy.*
  - **process temperature repeatable worldwide within 5 °C**
  - **within 1 fab / RTP supplier - 1 °C**
  - **compatible materials (O_2 sometimes an exception)**
  - **may identify non-temperature related processing problems**

- Disadvantages
  - **slow, not real time**
  - **single point for a process cycle**
  - **very costly**
  - **end user dependent**
  - **not easily traceable to freeze point standard -** *Accuracy is becoming more important, Portability of recipes between tools, between fabs, between vendors*

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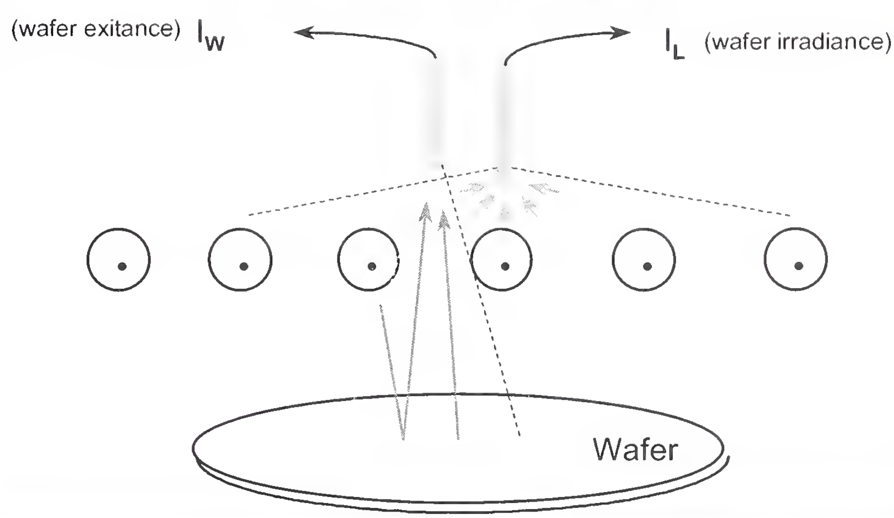
Schematic of External Configuration for Ripple Pyrometry



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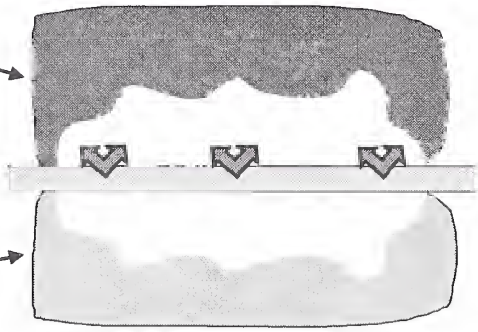
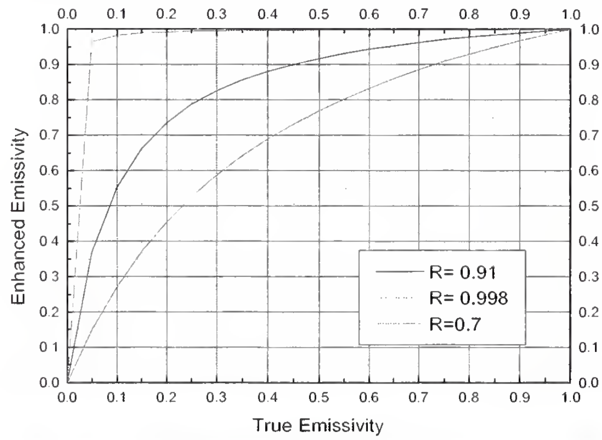
The Virtual Blackbody Cavity



The Conditions are met for Blackbody radiation

Pyrometer Surrounded by a Reflector Plate

- Depending on the reflectivity of the plate, *R*, ε_{True} is enhanced to ε_A
- For values of R approaching 1 (i.e. 100% reflection), ε_A approaches 1



Lightpipes / Optical Cables

- Connect / Disconnect
- Dependence of Cable Position, Polish
- Very Wide Field of View
  - Calibration Source must be close to L/P
  - Emissivity and uniformity must be known over wide angles
- Cold Calibrations
  - Characterize Target Radiation
- Hot Calibrations
  - Thermal Interaction with the Furnace
  - Contamination
  - Characterize Emissivity

17

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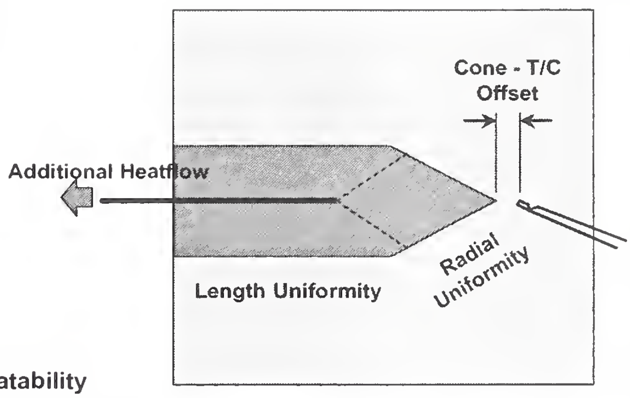
The Uncertainties of Hot Calibrations

- NIST Type S Uncertainty
- Emissivity of blackbody
- Cone/TC heat Transfer
- Added Heatflow
- Short Term Drift
- Long Term Drift
  - TC Hysteresis
- Contamination
- Self Emission
- Length Uniformity
- Radial Uniformity
- Lightpipe Position Repeatability



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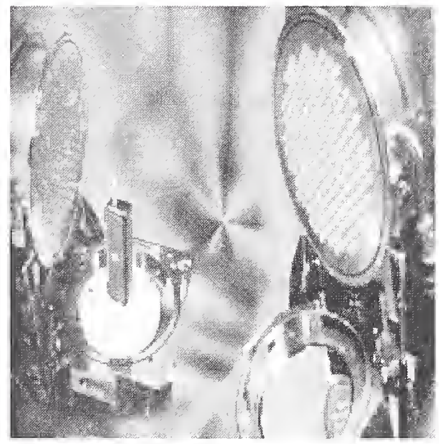
APPLIED MATERIALS

Cold Calibration Source

The TempMatch® tool is a portable transfer standard used for *in-situ* calibration of Optical Fiber Thermometers (OFT). This radiant source is a combination of LEDs, filters, and diffusers optically coupled to faithfully reproduce the blackbody spectrum for a single temperature over a limited bandwidth. The output intensity is feedback controlled for stability, and is nearly Lambertian for angles within the numerical aperture of the OFT. This tool is used to determine the OFT sensor factor (aperture correction) after installation and at periodic calibration intervals. Errors introduced due to the transfer standard only increased the total accuracy error of the OFT measurement from ± 1.2 °C to ± 1.75 °C. This performance is demonstrated to be sustained for a large population of instruments over a year's period of operation.



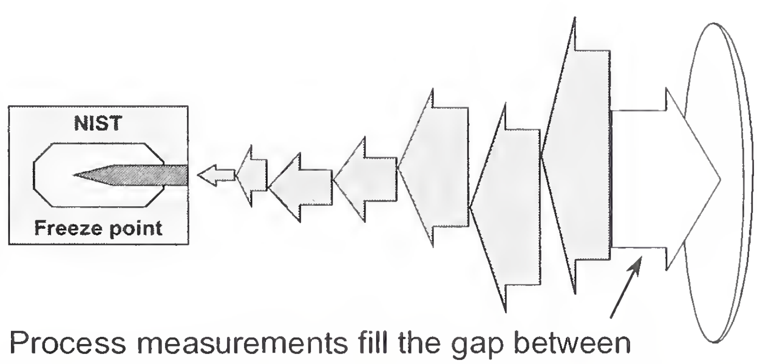
Why Traceability, and not just better Resolution?

- Better Process Control, Higher Yields
- Portability of Process Recipes
- Limits of process temperature scales
  - Cost
  - Time
- Moore's Law
  - Shorter process times
  - Higher ramp rates
  - Greater Temperature Accuracy

Accuracy Viewed from Different Points Along the Chain

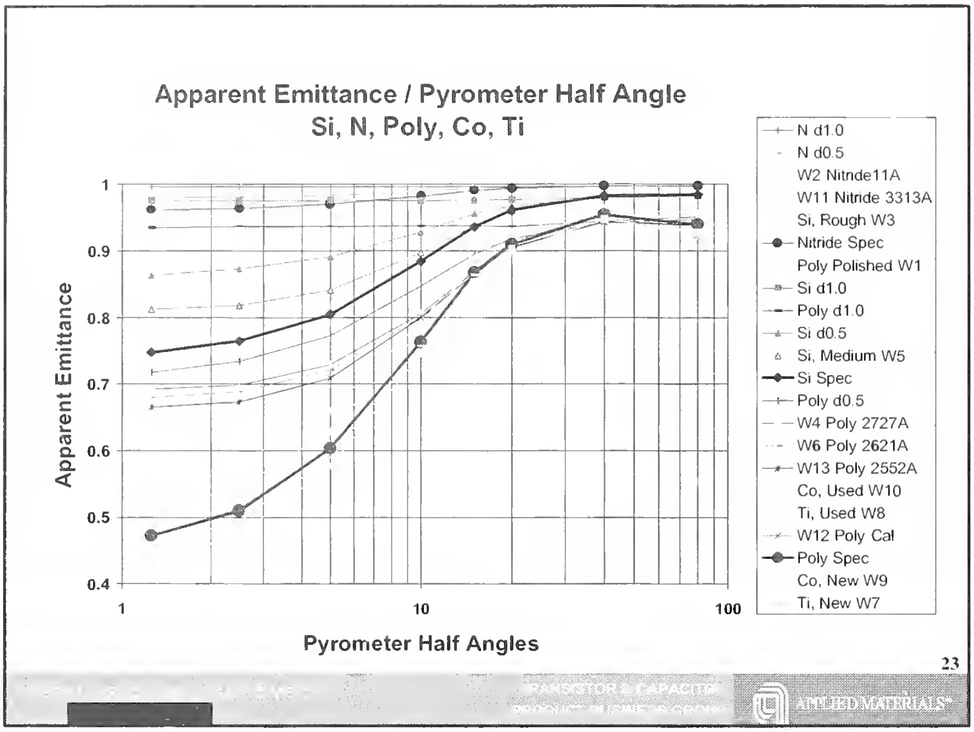
NIST	0.1 °C Type S T/C
Pyrometer Manufacturer (within pyrometer companies)	3.0 °C
RTP Manufacturer (between pyrometer companies)	6.0 °C
End User (systematic errors between RTP companies)	30 °C

Traceable Chain and Process Measurements



Process measurements fill the gap between instrument and wafer, but are not traceable.

Wafer


Apparent Emittance / Pyrometer Half Angle
Si, N, Poly, Co, Ti
Apparent Emittance
Pyrometer Half Angles
1
0.9
0.8
0.7
0.6
0.5
0.4
1
10
100
N d1.0
N d0.5
W2 Nitnde11A
W11 Nitride 3313A
Si, Rough W3
Nitride Spec
Poly Polished W1
Si d1.0
Poly d1.0
Si d0.5
Si, Medium W5
Si Spec
Poly d0.5
W4 Poly 2727A
W6 Poly 2621A
W13 Poly 2552A
Co, Used W10
Ti, Used W8
W12 Poly Cal
Poly Spec
Co, New W9
Ti, New W7
23
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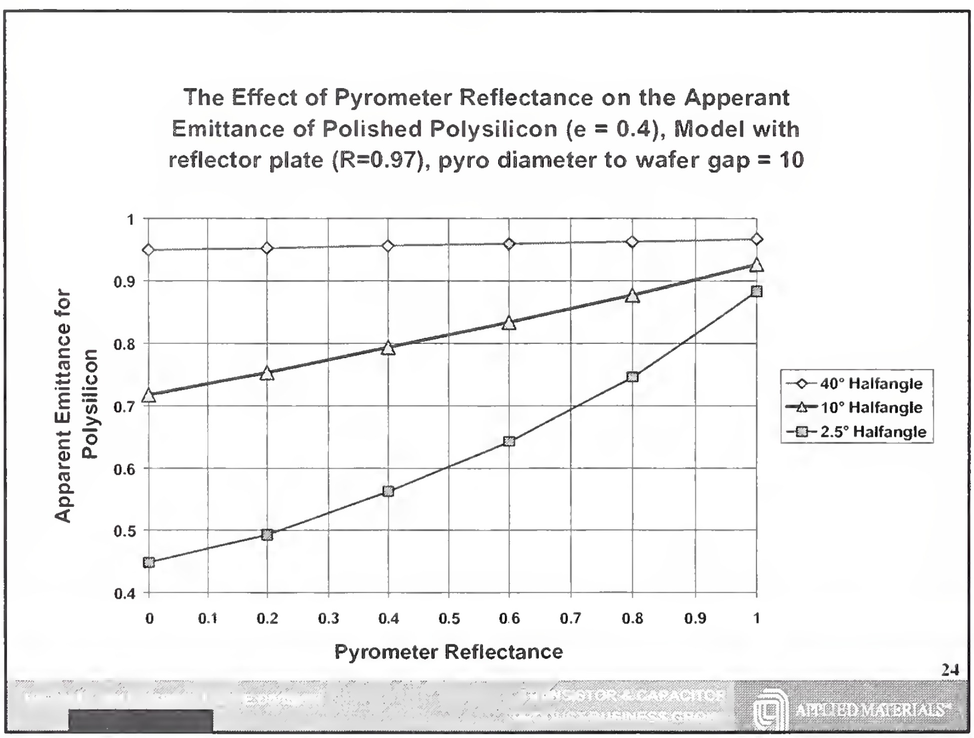
The Effect of Pyrometer Reflectance on the Apperant Emittance of Polished Polysilicon (e = 0.4), Model with reflector plate (R=0.97), pyro diameter to wafer gap = 10
Apparent Emittance for Polysilicon
Pyrometer Reflectance
1
0.9
0.8
0.7
0.6
0.5
0.4
0
0.1
0.2
0.3
0.4
0.5
0.6
0.7
0.8
0.9
1
40° Halfangle
10° Halfangle
2.5° Halfangle
24
APPLIED MATERIALS

Recommendations

1. Develop an understanding of the heat transfer issues involved in your method of calibration

2. ANSI/NCSL Z540 Standard (1994)
   Documentation for Calibration Laboratories
   Traceability, Uncertainty Analysis

3. Use real time *in-situ* emissivity measurements to determine wafer temperature.

4. Don't ignore the effect of the pyrometer on the measurement

5. Common problems and measurement error
   Inadequate heat transfer model for the application
   Not routinely verifying calibrations with NIST traceable standards
   Inadequate monitor wafer quality (cleaning of recycled wafers)
   Contamination of optical components
   Operator errors

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APPLIED MATERIALS

References and Bibliography

- ***Temperature Measurement Issues in Rapid Thermal Processing*** ,DeWitt D.P., Sorrell F.Y., Elliott J.K.,, Mat. Res. Soc. Proc., **470**, edited by Riley, Gelpey, Roozeboom, Saito, MRS, San Francisco, 1997, pp 3..15

- ***The Challenges of Temperature Measurement in the Semiconductor Industry***. B. E. Adams, TEMPMEKO'99, J. F. Dubbeldam and M. J. de Groot, Eds., Vol 1, p.3, NMI Van Swinden Laboratorium - Delft, The Netherlands (1999).

- ***Rapid thermal Annealing and Oxidation of Silicon Wafers with Back-Side Films*** Fiory A.T.,, Mat. Res. Soc. Proc., **470**, edited by Riley, Gelpey, Roozeboom, Saito, MRS, San Francisco, 1997, pp 49..56

- ***Advances in Temperature Measurement and Control for RTP***, Peuse B., Yam M., Bahl S.,, Proc. 5th Intl. Conf. Adv. Thermal Processing of Semiconductors,edited by Fair, Green, Lojek, Thakur, RTP'97, New Orleans, 1997, pp 358..365

- ***Emissometer U.S. Patents 5660472, 5755511 European EPA0612862,***

- ***Calibration of OFTs in Production***. R. R. Dils, RTP'99, (get full paper from Sekidenko Inc.)

- ***Determining the Uncertainty of Wafer Temperature Measurements Induced by Variations in the Optical Properties of Common Semiconductor Materials***, B. E. Adams, A. Hunter, M.Yam and B. Peuse, ECS'2000

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APPLIED MATERIALS

MEASUREMENT OF WAFER SURFACE TEMPERATURE USING THERMOCOUPLES AND TEMPERATURE CALIBRATION OF RTP EQUIPMENT

B. Lojek
ATMEL Corporation

BAD DATA LOOK AS BELIEVABLE AS GOOD DATA
alias
WAFER TEMPERATURE MEASUREMENT MATTERS!

ATMEL
COLORADO SPRINGS

NIST
GAITHERSBURG (09/19/00)

1

WHY IS IT IMPORTANT TO KNOW WAFER TEMPERATURE ?
and
WHY IS MATCHING THE SHEET RESISTANCE NOT GOOD ENOUGH?

MOST PHYSICAL MECHANISMS INVOLVED IN ANNEALING, DIFFUSION, AND OXIDATION EXHIBIT A VERY STRONG TEMPERATURTE DEPENDENCE. (For example, a change of approximately 80 °C results in a change of diffusivity of common Si dopants, about one order of magnitude).
A WRONG CONCLUSION ABOUT PHENOMENA MAY BE DRAWN IF ACTUAL WAFER TEMPERATURE IS NOT KNOWN.

IN A MULTI FAB MANUFACTURING ENVIRONMENT, MISSING KNOWLEDGE OF ACTUAL PROCESSING TEMPERATURE INCREASES THE COST AND TIME OF TECHNOLGY TRANSFER

THE SHEET RESISTANCE MEASUREMENT CAN LEAD TO ERRONEOUS RESULTS FOR SHORT ANNEALING TIMES AND ARE FAIRLY INSENSITIVE FOR LONG TIME ANNEALING. THE MATCHING OF SHEET RESISTANCE DOES NOT GUARANTEE THAT OTHER MATERIAL PROPERTIES ARE THE SAME.

ATMEL
COLORADO SPRINGS

NIST
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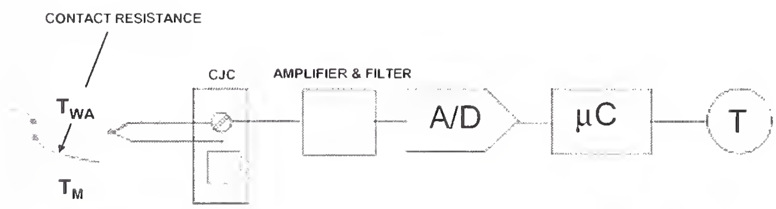
2

TYPICAL INSTRUMENTATION SETUP FOR WAFER TEMPERATURE MEASUREMENT

T_W

REQUIRED "DVM" SENSITIVITY

TC	SEEBECK COEFFICIENT [µV/°C]	"DVM" SENSITIVITY FOR 0 1 °C [µV]
K	40	4 0
R	7	0 7
S	7	0 7



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WAFER TEMPERATURE HIERARCHY:

T_W - UNDISTURBED WAFER TEMPERATURE - **THE TEMPERATURE OF THE WAFER WHEN NO DISTURBANCE ARISES FROM THE MEASUREMENT PROCEDURE**

T_{WA} - AVAILABLE WAFER TEMPERATURE - **WAFER TEMPERATURE WHEN TRANSDUCER AND MEASUREMENT SYSTEM ARE IN PLACE**

T_A - ACHIEVED WAFER TEMPERATURE - **THE WAFER TEMPERATURE SENSED BY TRANSDUCER**

T_M - OBSERVED WAFER TEMPERATURE - **THE WAFER TEMPERATURE INDICATED BY MEASUREMENT SYSTEM**

T - CORRECTED WAFER TEMPERATURE - **THE WAFER TEMPERATURE AFTER APPLYING ALL CORERECTION (LINEARIZATION, INTERPOLATION etc.)**

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ERROR BUDGET

- INTRINSIC ERROR OF THERMOCOUPLE
- ERROR DUE TO THERMOCOUPLE - WAFER ASSEMBLY
- INSTRUMENTATION ERRORS
- ERRORS DUE TO STRUCTURAL CHANGES OF IMPLANTED LAYERS AT WAFER SURFACE

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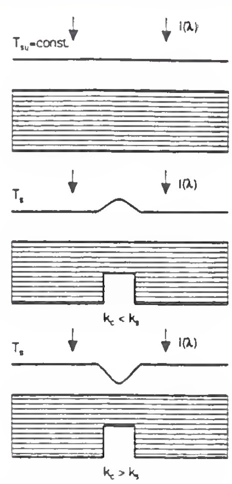
THE PERTURBATION OF THE WAFER TEMPERATURE DUE TO DIFFERENT THERMAL CONDUCTIVITY IN THE CAVITY



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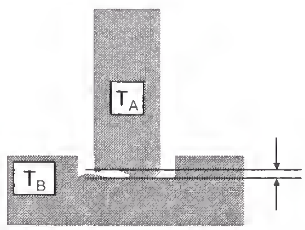
THERMAL CONTACT RESISTANCE R_{tc}



DUE TO SURFACE ROUGHNESS, TWO BODIES TOUCH AT ONLY A FEW DISCRETE SPOTS.

COMPONENTS OF R_{tc}:

1) SOLID TO SOLID CONDUCTION AT SPOTS IN CONTACT
2) RADIATION IN THE VOID SURFACES CREATED BY THE CONTACT

THE CONTACT RESISTANCE IS DOMINANT THERMAL RESISTANCE WHEN HIGH THERMAL CONDUCTIVITY MATERIALS ARE INVOLVED IN CONTACT. TYPICAL MAGNITUDE OF R_{tc} FOR TC WIRE WITH DIAMETER 80-100 μm IS 800-5000 °C/W. SUCH MAGNITUDE OF R_{tc} RESULTS IN 4 - 20 °C DIFFERENCE BETWEEN AVAILABLE WAFER TEMPERATURE AND ACHIEVED WAFER TEMPERATURE.

[T.Borca-Tasiuc et.al UCLA, 1998, B.Lojek, RTP'95]

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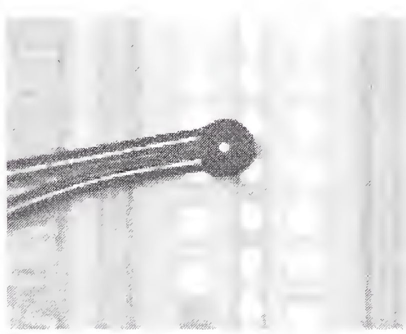
"CLASSICAL" TC
(WIRE DIAMETER 80 μm)



TC WITH FLAT BEAD
MINIMIZING THERMAL COTACT RESISTANCE

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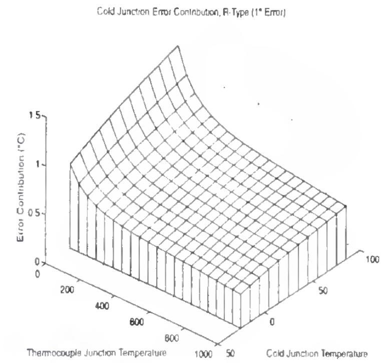
FOR MOST PC BASED TEMPERATURE ACQUISITION BOARDS, THE ERROR ASSOCIATED WITH COLD JUNCTION COMPENSATION IS BY FAR A DOMINANT INSTRUMENTATION ERROR



TC TEMPERATURE ERROR ASSUMING
+/- 0.5 °C ACCURACY IN CJC TEMPERATURE

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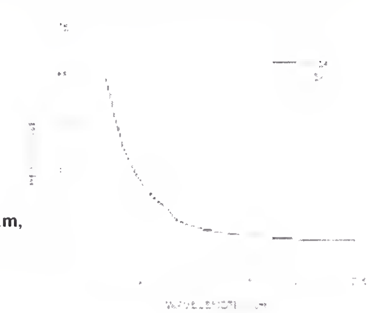
POWER ABSORBED BY WAFER DEPENDS ON THE REFLECTIVITY AND ABSORPTION OF THE WAFER

Absorbed power for uniformly doped wafer of thickness t_w is given by:

$$P_{abs} = \int_{\lambda 1}^{\lambda 2} (1-R(\lambda)) I_o(\lambda)[1-\exp(-\frac{\alpha(\lambda)}{t_w})] d\lambda$$



IN RANGE OF WAVELENHGTH 0.4 to 1.5 μm, RYSTALIZATION FROM α-Si TO c-SI IS ACCOMPANIED BY A NON-REVERSIBLE REFLECTIVITY DECREASE.

[FROM S. ADACHI, GUNMA UNIVERSITY, 1998]

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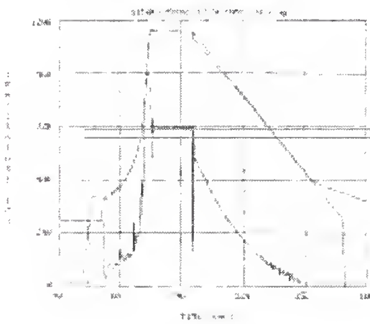
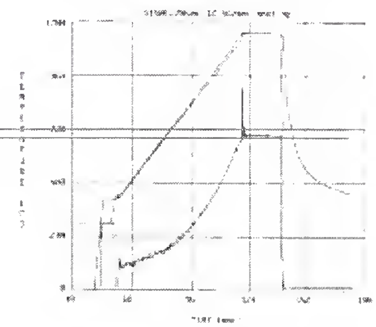
IMPACT OF IMPLANTED LAYERS ON THE WAFER TEMPERATURE MEASUREMENT

(As 1E14@20keV)





FOR GIVEN CALIBRATION DATA, SET-POINT POWER IS FUNCTION OF THE HEATING RATE. (Calibration data has been acquired for heating rate 12.5 °C/sec, therefore the run with faster heating rate indicate a wrong temperature at set point)

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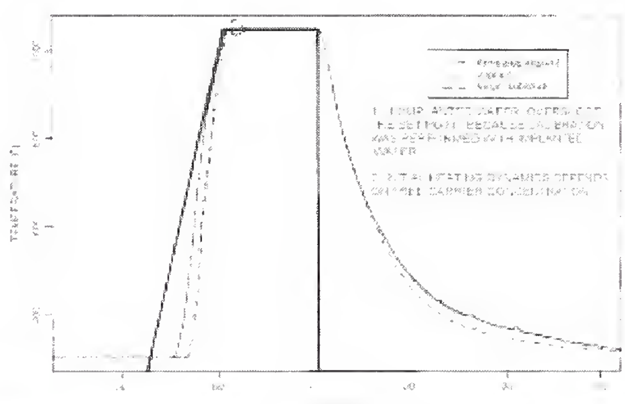
IMPACT OF IMPLANTED LAYERS ON THE WAFER TEMPERATURE MEASUREMENT



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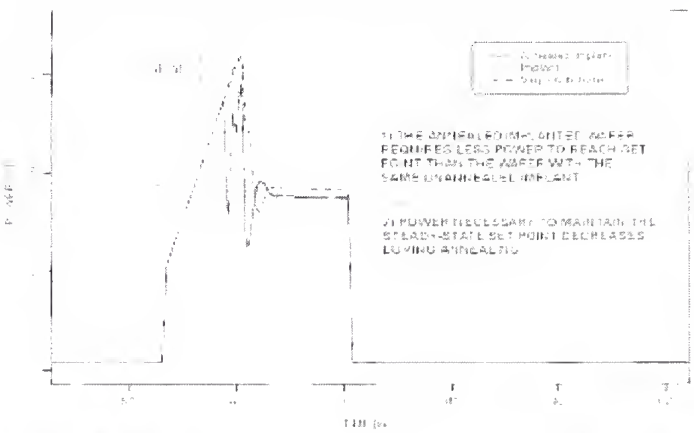
IMPACT OF IMPLANTED LAYERS ON THE WAFER TEMPERATURE MEASUREMENT



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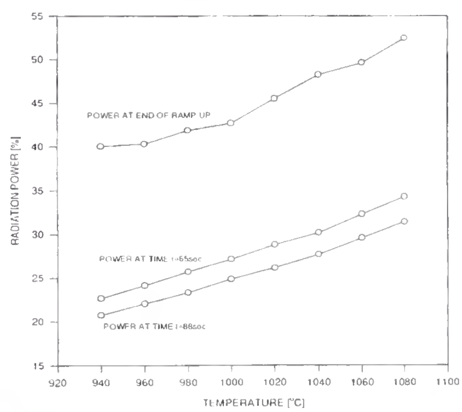
IMPACT OF IMPLANTED LAYERS ON THE WAFER TEMPERATURE MEASUREMENT

RAMP 50 °C/sec FROM 400 °C TO SET POINT TEMPERATURE WITH 30 SEC ANNEAL (As IMPLANT 1E16@20keV)



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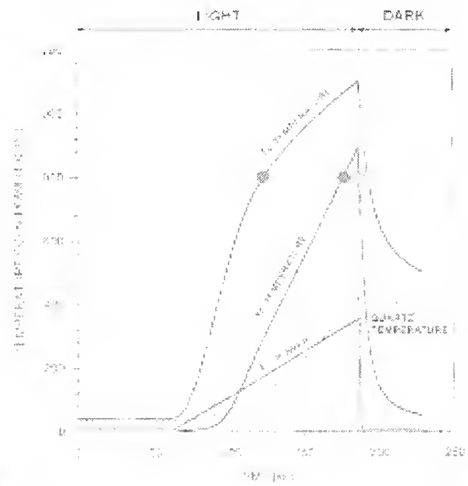
TEMPERATURE CALIBRATION OF RTP SYSTEM USING WAFER WITH EMBEDDED TC



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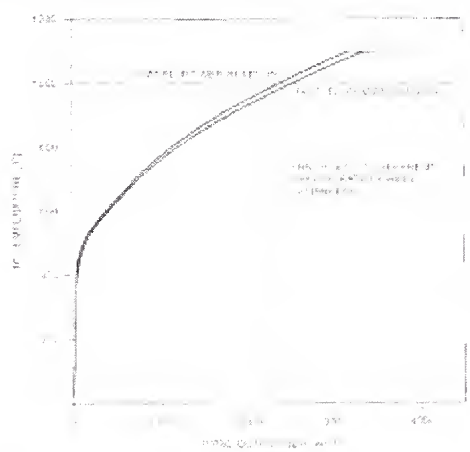
TEMPERATURE CALIBRATION OF RTP SYSTEM USING WAFER WITH EMBEDDED TC



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CONCLUSIONS

WHAT CANNOT BE MEASURED,
CANNOT BE CONTROLLED !

- TC CALIBRATION SHOULD BE PERFORMED UNDER THE SAME CONDITIONS AS THE RECIPE, WHERE CALIBRATION DATA IS USED
- CALIBRATION WAFER SHOULD BE USED ONLY ONCE
- CALIBRATION WAFER SHOULD BE IDENTICAL TO THE PRODUCT WAFER
- IF "INAPPROPRIATE" WAFER IS USED FOR CALIBRATION (FOR EXAMPLE, REPEATEDLY ANNEALED WAFER, DIFFERENT SUBSTRATE, POORLY DESIGNED TC, etc.) THE TEMPERATURE MEASUREMENT ERROR MAY BE AS LARGE AS 20 – 30 °C

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CONCLUSIONS (cont.)

WHAT CANNOT BE MEASURED,
CANNOT BE CONTROLLED !

- DIGITAL ELECTRONICS INSTRUMENTATION HAS CREATED AN ILLUSION THAT VERY ACCURATE THERMOCOUPLE THERMOMETRY IS RELATIVE EASY AND ROUTINE MEASUREMENT
- THE THERMOCOUPLE SURFACE TEMPERATURE MEASUREMENT OF THE WAFER WHICH IS NOT IN THERMAL EQUILIBRIUM WITH SURROUNDING AMBIENT IS A CHALLENGING PROBLEM WHERE SPECIFIC PHENOMENA (i.e. TC INSTALLATION, TC CONTACT RESISTANCE, WAFER PROPERTIES, etc.) DETERMINE ACCURACY OF MEASUREMENT
- IF PROPERLY EXECUTED, THE TC TEMPERATURE MEASUREMENT IS VERY ACCURATE (IF NOT THE MOST ACCURATE) METHOD OF SURFACE TEMPERATURE MEASUREMENT OF THE WAFER UNDER THERMAL NON-EQUILIBRUIM CONDITIONS

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Thermal Characterization of Batch Furnaces using Thermocouple Instrumented Wafers

Cole Porter and Karl Williams
Silicon Valley Group, Thermal Systems Division

Workshop on
Temperature Measurement
of Semiconductor Wafers
Using Thermocouples

RTP 2000 Conference
September 19, 2000

1

Thermal Systems

Overview

- **What**
  - Batch Furnace configuration
  - Batch furnace temperature measurement
- **Why**
  - Thermal stresses in Si
  - Process chamber vs. wafer temperature
  - Heat transfer in batch furnace
- **How**
  - T/C wafer configuration
  - T/C wafer installation
- **Issues**
- **Conclusions**
- **References**

2

Thermal Systems

Batch Furnace Configuration

- High purity dual-wall quartz tube process chamber
- Wafer fixture "boat"
- Pedestal, supports the wafer boat.
- Process chamber positioned vertically inside the heater element
- Gas injection is via MFC through manifold assembly

3

Thermal Systems

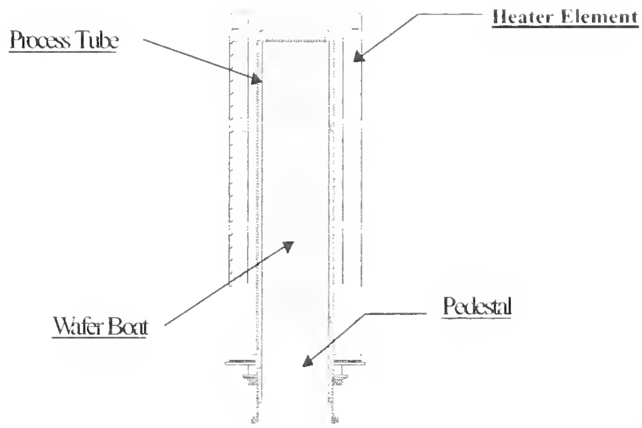
Temperature control

- Furnace temperature is monitored and controlled via "profile" thermocouples located inside the process chamber in each of five control zones of the heater element
- Profile thermocouples provide an approximation of the wafer stack temperature
- "Spike" thermocouples are positioned outside of the quartz process chamber in close proximity to the element windings in each of the five control zones
- Spike thermocouples provide an approximation of the heater element temperature

4

Thermal Systems

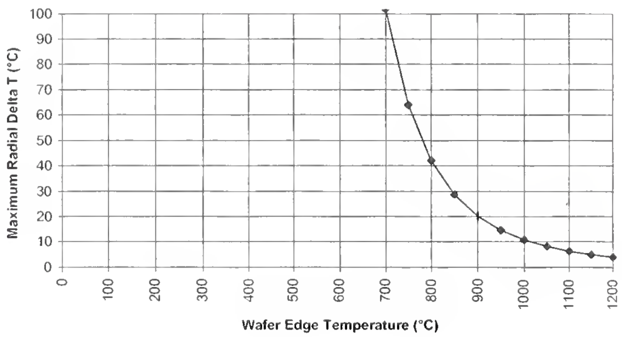
Batch Furnace Configuration



Thermal stress

- Rapid Vertical Processor (RVP) furnace systems can ramp at rates in excess of 75°C/min
- In a batch furnace, ramp rates in this range can thermally stress wafers causing slip and wafer warpage
- A critical effect during fast-ramp processing is the radial delta temperature (RDT) within each wafer during ramp up and ramp down
- During ramping conditions, wafer edges will heat and cool at a higher rate than wafer centers

Slip Curve



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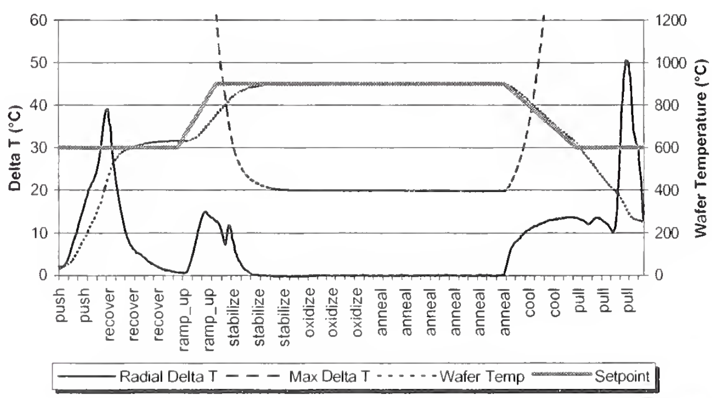
Thermal Systems

Wafer temperature, process

RDT/Slip curve



8

Thermal Systems

Thermal stress, Si

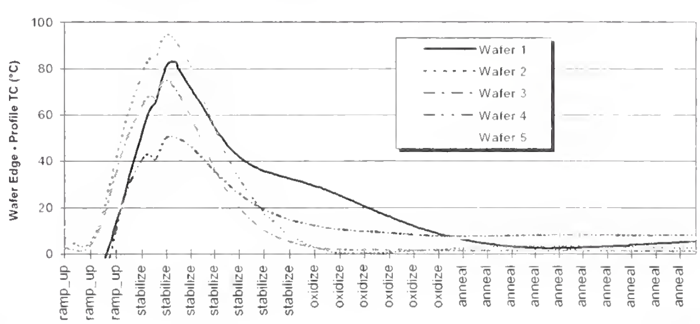
- Thermal stress must be held below the plastic deformation limit of Si
- Slip dislocations may be generated resulting in lower device yields
- The maximum allowable Radial Temperature Delta (RDT) that will produce slip in Si is well known and documented
- RDT Slip limits decrease as temperature is increased
- The use of t/c wafers to understand actual wafer temperatures in this case is a very important tool
- The knowledge gained using t/c wafers feed into the final product, process chamber and recipe design

9

Thermal Systems

Profile t/c vs wafer temperature

- Under ramping conditions the profile t/c signal can be far from actual wafer temperatures
- Profile t/c to wafer temperature errors can be as large as 100°C under fast ramping conditions



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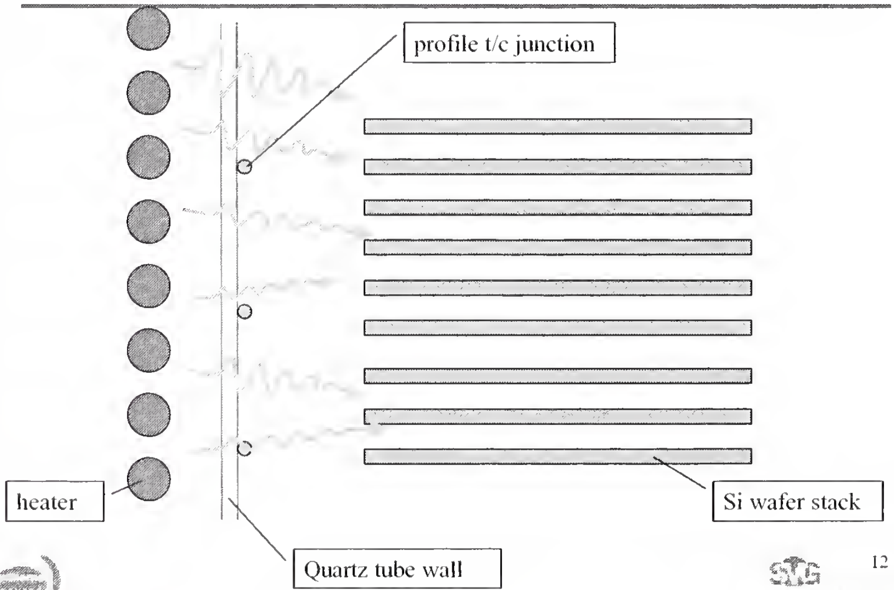
Thermal Systems

Batch Furnace heat transfer

- At higher temperatures heat transfer is predominantly via radiation
- Path is from heater to the absorbing wafer stack
- Passes through the semitransparent quartz where the profile t/c is positioned.

SVG Thermal Systems 11

Heat transfer via radiation



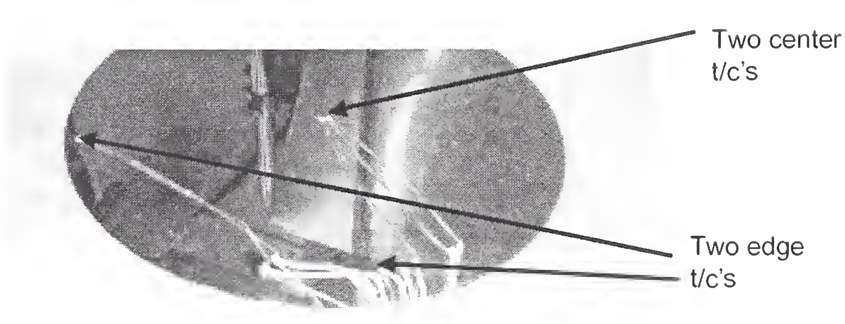
SVG Thermal Systems 12

T/C wafer configuration

- T/C placement
  - 2 center 2 @ 6mm from edge
  - 1 center and 1 edge is monitored
  - Extra center and edge provide redundancy
- Wafer positioning in wafer stack
  - Optimal locations to represent product wafer population
  - 5 wafers used
  - Spaced equidistant within the product zone
  - All other slots occupied with filler wafers

SVG Thermal Systems 13

T/C location on wafer



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T/C wafer, wire configuration

- Harnessing/wire insulation
  - Micro quartz tubing at wafer surface
  - Stress relief posts at wafer edge
  - Silica braided insulation from wafer edge to bottom of reactor chamber
  - Polyimide tape insulation at area of door seal
  - Teflon tubing insulation up the mini connectors
  - Braided silica over-sleeving

Thermal Systems 15

T/C wafer, wire configuration

Thermal Systems 16

T/C wafer, substrate and signal

- Wafers
  - Prime quality <100>
  - >7000A thermal oxide, prevents platinum wire breakage due to Pt-Si silicidation
- Signal processing
  - Cu t/c extension wire harnessed from mini connectors to signal conditioners
  - On board AD signal conditioners convert millivolt signal to 0-5 volt
  - 0-5V signal processed in temp control board

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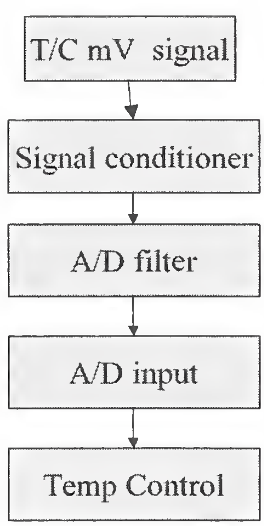
Thermal Systems

T/C wafer, signal path



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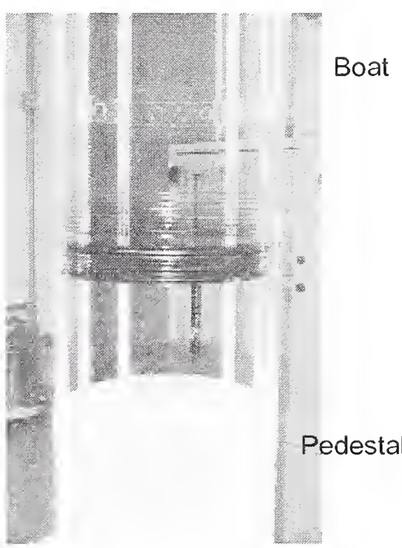
Thermal Systems

T/C wafer, installation

- Installation
  - Wafer installed in empty boat slot using tweezers
  - Edge t/c's positioned away from wafer support rail
  - Wire leads are positioned vertically against wafer stack
  - Silica braided string used to secure leads against boat rails
  - Polyimide flat cable positioned across 'o' ring surface
  - Leads are secured using polyimide adhesive tape outside chamber
  - Strain relief fasteners applied to teflon section of leads at door surface

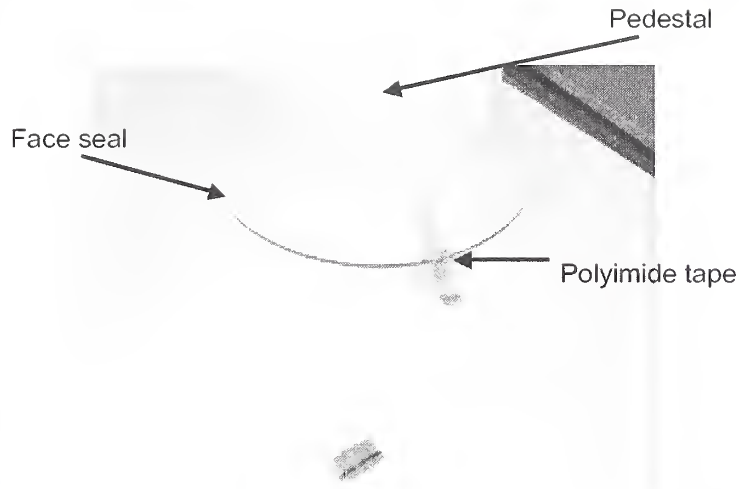
SVG Thermal Systems 19

T/C wafer, installation



SVG Thermal Systems 20

T/C wafer, installation



21

Thermal Systems

T/C wafer, issues

- High temp Insulation material
  - Particle generation, abrasion
  - Lifetime
  - Reliability
  - Handling
- Wafer breakage during shipping
  - Container
  - Wafer support
  - Wafer size
  - Shipper

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Thermal Systems

T/C wafer, issues

- Signal noise
  - Wire routing within process chamber
  - Filtering

- High temp >1050°C
  - Type B?
  - Reliability?
  - Longevity?

Thermal Systems 23

Conclusions

- T/C wafers are a valuable tool for batch furnace diagnostics
- Furnace chamber thermal characteristics are understood
- Profile t/c vs wafer temperature error is known
- Transient wafer dynamics are measured real time
- Thermal stress is characterized
- T/C wafer configurations for up to 1050°C processing established and reliable
- Future
  - >1050°C
  - insulation
  - packaging

Thermal Systems 24

References

1 Christopher Ratliff, Cole Porter, Allan Laser, Anthony Dip, Rapid Vertical Processor for Fast-Ramp Diffusion and Oxidation Applications, RTP 97 Conference

2 Robert H. Nilson and Stewart K Griffiths. Sandia National Laboratories, Scaling Batch Processes for Large Wafer Diameters, Second Large Diameter Wafer Thermal Issues Conference, Sept. 1996

NATIONAL INSTRUMENTS™

Computer-Based Temperature Measurement Systems

Bakul Damle, Group Manager

Workshop on
Temperature Measurement
of Semiconductor Wafers
Using Thermocouples

RTP 2000 Conference
September 19, 2000

www.ni.com

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Agenda

- Computer-based measurement of Thermocouples
- Filtering, auto-zero, Cold-Junction Compensation (CJC), open-thermocouple detection
- The right connectivity is important
- Software makes the difference
- Computer-based infrared vision systems
  - a possible alternative to thermocouple acquisition

2

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Computer-Based Approach

- Computer-based approach is very common
  - PCI boards (in desktop PC)
  - USB (instruments external to the PC)
  - PXI/CompactPCI (modular instruments)
- Commercially available high-resolution A to D converters
  - Driven by consumer electronics industry
- Versatile, fast, low cost
- Challenges
  - Same pitfalls as other systems

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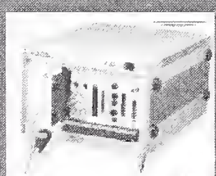
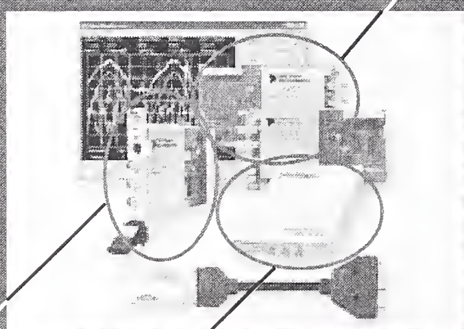
Examples of PCI, USB, PXI/CompactPCI

PCI



PXI



PXI/CompactPCI

USB

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Filtering

- Pre-digitizing filtering is necessary
  - to eliminate high-frequency noise
  - to eliminate powerline noise
  - to avoid aliasing
- Post-digitizing filtering in software
  - can improve quality of measurements
  - cannot replace pre-digitizing hardware filtering

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NATIONAL INSTRUMENTS

Cold Junction Compensation

- Thermocouples make relative measurements
  - CJC converts them into absolute measurements
- CJC sensor must be at same temperature as cold junction
  - System must be in isothermal with thermocouple connectors
- Errors reading CJC sensor
  - Measurement errors will affect CJC
  - This must be taken into account

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Offset and Gain Errors

- Error due to offset and gain errors in amplifier
  - Impossible to eliminate completely
  - Use auto-zero
    - short one channel, measure and subtract the offset
  - Compensates for drifts over time
- Check the common mode voltage of the thermocouple
  - If too high, you have to change instrument
  - Converter with isolated front-end will help

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Open-Thermocouple Detection

- Check your thermocouple
  - If it is open, your measurements are incorrect
- How are open thermocouples detected?
  - Measure the thermocouple resistance
    - If it is too high, chances are the thermocouple is broken

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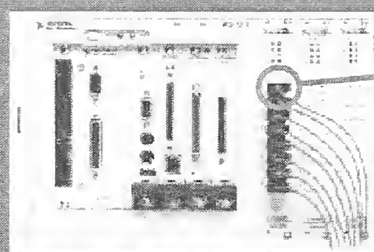
Connectivity

- Choose the right connectivity
  - Mini-plugs (time is money)
    - mini-plugs can make your setup and maintenance much faster
  - Modular terminal blocks
    - Provide fast maintenance operations



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Software

- Software is core to the application
  - A measurement-oriented language provides
    - Internet connection
    - Database (Oracle, Access etc) connectivity
    - "*Measurement intelligence*"
    - Great analysis functions
- Measurement-oriented languages
  - LabVIEW™ for graphical approach
  - Measurement Studio™ for LabWindows™/CVI, C++, Visual Basic

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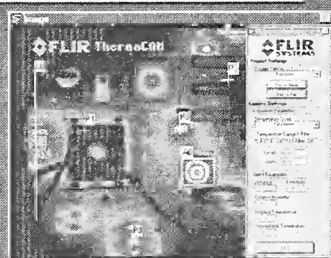
Vision-Based Systems - An Alternative-

- Vision-based systems
  - Can provide an alternative solution
  - Recent technological breakthroughs for cameras
    - Affordable and low-maintenance thermal cameras
  - Map the entire wafer(s) at once (equivalent of 76.000 thermocouples read 60 times a second)
  - Same software approach (LabVIEW™ or Measurement Studio™)
  - ni.com/imaq

Vision Systems - Examples -

Example 1:
Using LabVIEW™ and infrared cameras to map temperature on a semiconductor wafer. Hotter temperatures reflect or radiate more infrared energy, and the cameras measure these differences and display them in varying colors

Full description **http://ni.com/imaq/thermal.htm**



Example 2:
ThermoMap™ system, a micron-resolution thermal imaging system using liquid-crystal sensors with LabVIEW™ and IMAQ ™ Vision software for thermal mapping of semiconductor devices.

Solution developed by **Tempronic Corp.**

Full description **www.ni.com/semicon**

Conclusions

- Thermocouple measurements are easily made with computer-based approach
- Same "do's and don'ts" of traditional systems
- The right connectivity is important
- Software makes the difference
- Vision-based systems can provide an interesting alternative

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NATIONAL INSTRUMENTS

Instrumentation Issues for Thermocouple Measurements

Tom Hayden
Manager of Sales Training and Support
Keithley Instruments, Inc.
Cleveland, OH

Workshop on
Temperature Measurement
of Semiconductor Wafers
Using Thermocouples

RTP 2000 Conference
September 19, 2000

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1

Instrumentation for Temperature

Major sources of error in most systems

- Sensor and Thermal Contact with Subject (covered elsewhere in conference).
- Cold Junction Reference Error (0.1° to 5.0°C)
- Noise Pick-Up – mostly 60 Hz (0.01° to 0.2°C)
- V to T Conversion Errors (0.02° to 0.4°C)
- V Measurement Errors (0.1° to 2.0°C)

Note: Individual error sources are rarely specified – usually just the sum.

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Instrumentation for Temperature

Additional Problems with Rapid Thermal Measurements

- Thermal Latency in Sensor (covered elsewhere in conference).
- Measurement Latency

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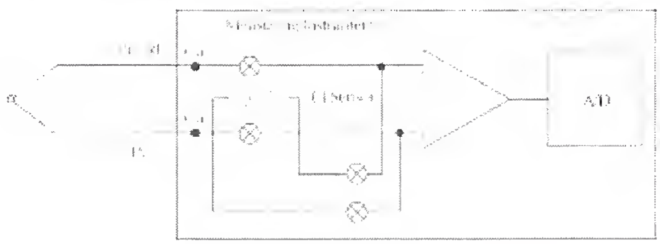
Instrumentation for Temperature



- CJ Sensor – typically Thermistor, Semiconductor Sensor or RTD
- Sensor accuracy is typically 0.1° to 0.2°C
- Additional errors can be due to gradient between sensor and actual junction
- Can be minimized by isothermal bars/blocks and/or removal from sources of heat

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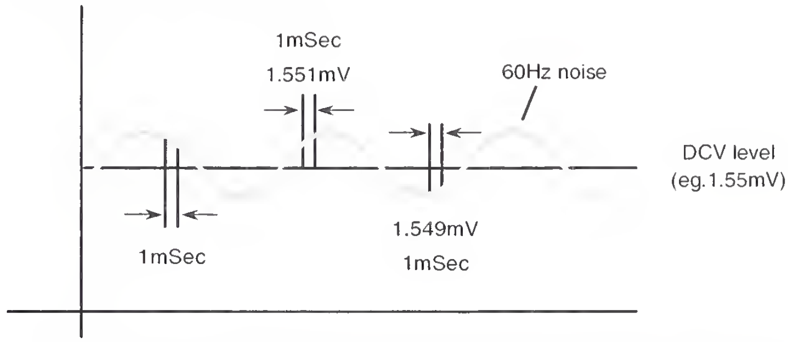
4

Instrumentation for Temperature

Noise (60Hz) pick-up.



1) **With type K T/C (40µV/°C), just 1µV noise = 0.025° error**
2) **With type R or S (11-13 µV/°C), 1µV = 0.08°C**

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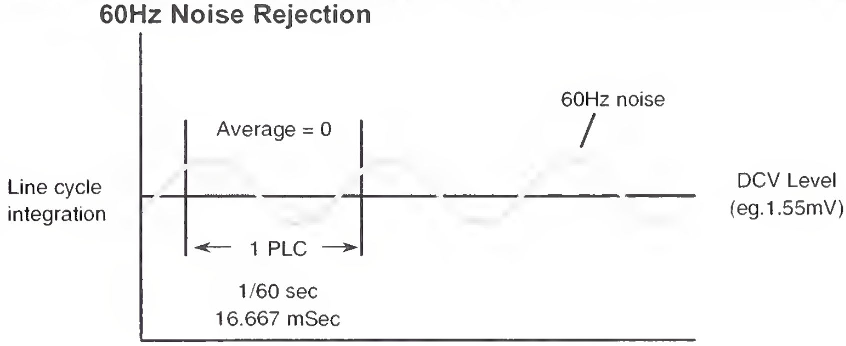
5

Instrumentation for Temperature

60Hz Noise Rejection



Line cycle integration (16.66 mSec increments) can reduce this error by 60-80 db (1000 – 10,000 to 1).
Common method used in 90+% of multimeters and some A/D Boards.

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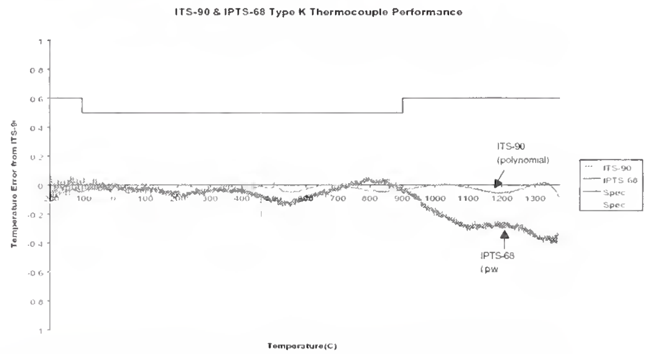
6

Instrumentation for Temperature

Voltage to Temperature Conversion Errors



- Many methods: look up table, piecewise linear, polynomial
- Piecewise linear can be 0.02°C to 0.2°C depending on how many segments
- IPTS-68 vs. ITS-90 can add 0.1°C to 0.4°C additional conversion error – especially above 900°C

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7

Instrumentation for Temperature

Volts Measurement Errors

- Type R, S Thermocouples are 11 to 13μV/°C
- Type K Thermocouple is ~40μV/°C
- Most measurements are done on a 100mV range
- A good 6-1/2 digit DMM has about a ±50ppm of range spec (plus a ±50ppm of reading)
- This translates to about 5-6μV of error over the 0 to 10mV range of input signals
- This corresponds to about 0.5° with R/S and 0.12°C with K

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8

Instrumentation for Temperature

Additional errors for Rapid Thermal Measurements

Measurement Latency

- 0 to 1000° in 5 sec = 0.2°/mSec
- A 17mSec measurement (1PLC for good, accurate measurement)
- 17 x 0.2 = 3.4° ramp during each measurement
- Reading will be approx AVERAGE temp over this time which should be approximately equal to the specific temperature about 8-10mSec before the end of the reading.

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9

Temperature Profiling of Ripple Pyrometers with Thermocouple Wafers

A. T. Fiory

Bell Laboratories, Lucent Technologies, Inc., Murray Hill, N.J.

This presentation briefly reviews a set-up procedure for ripple pyrometers in rapid thermal annealing of silicon wafers. Ripple pyrometers are used to sense wafer temperature with in-situ compensation for emissivity variations caused by surface films. Lucent's ripple pyrometer probe has two sensors for detecting thermal and reflected radiation from the wafer and heating lamps. Temperature profiling determines the settings of sensitivity parameters for the probe by heating wafers prepared with a range of emissivities and wired with embedded thermocouple junctions.

NIST Thermocouple Workshop
RTP'00 Conference
September 19, 2000

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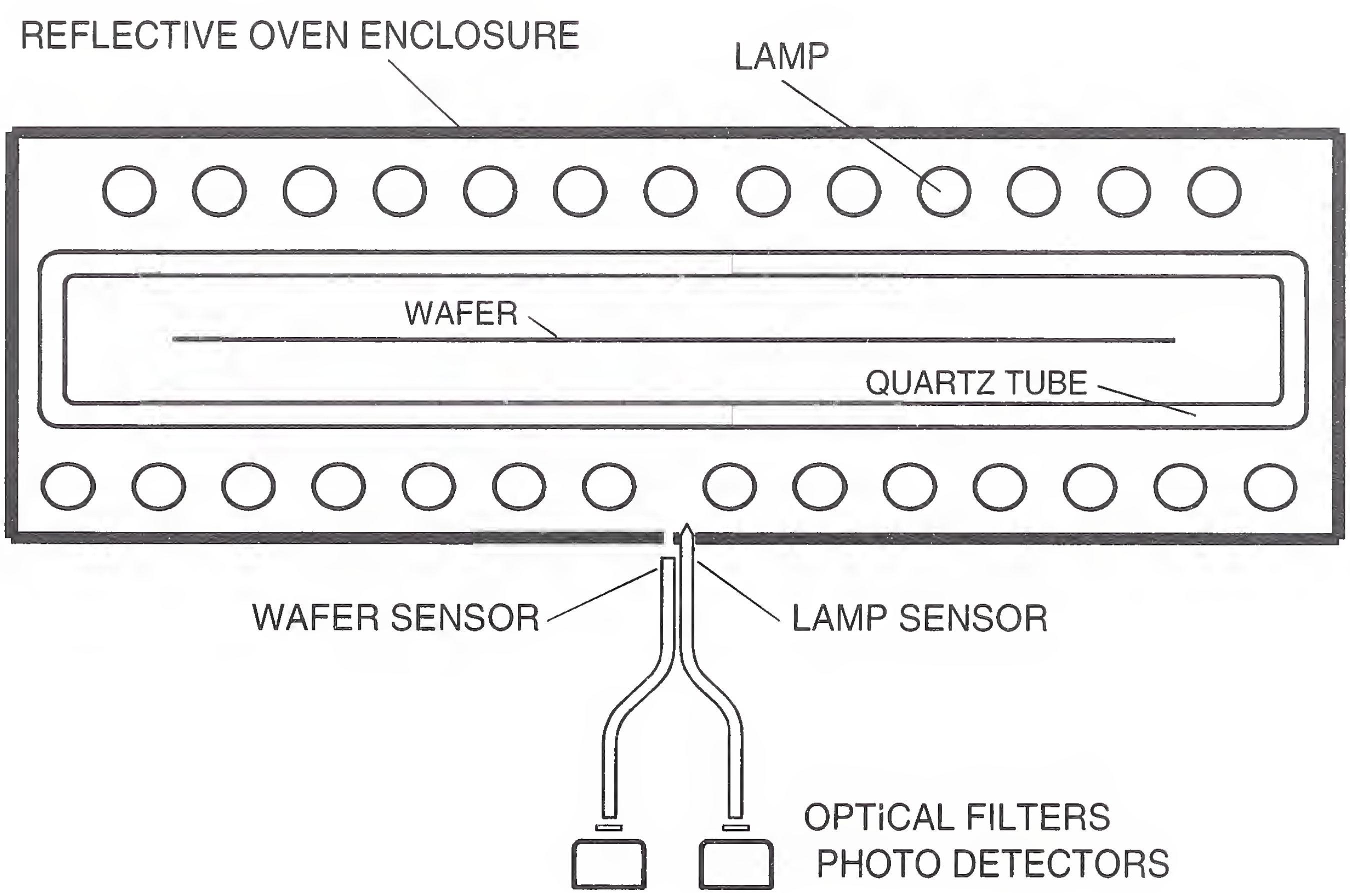
Schematic RTA oven with ripple pyrometer probe



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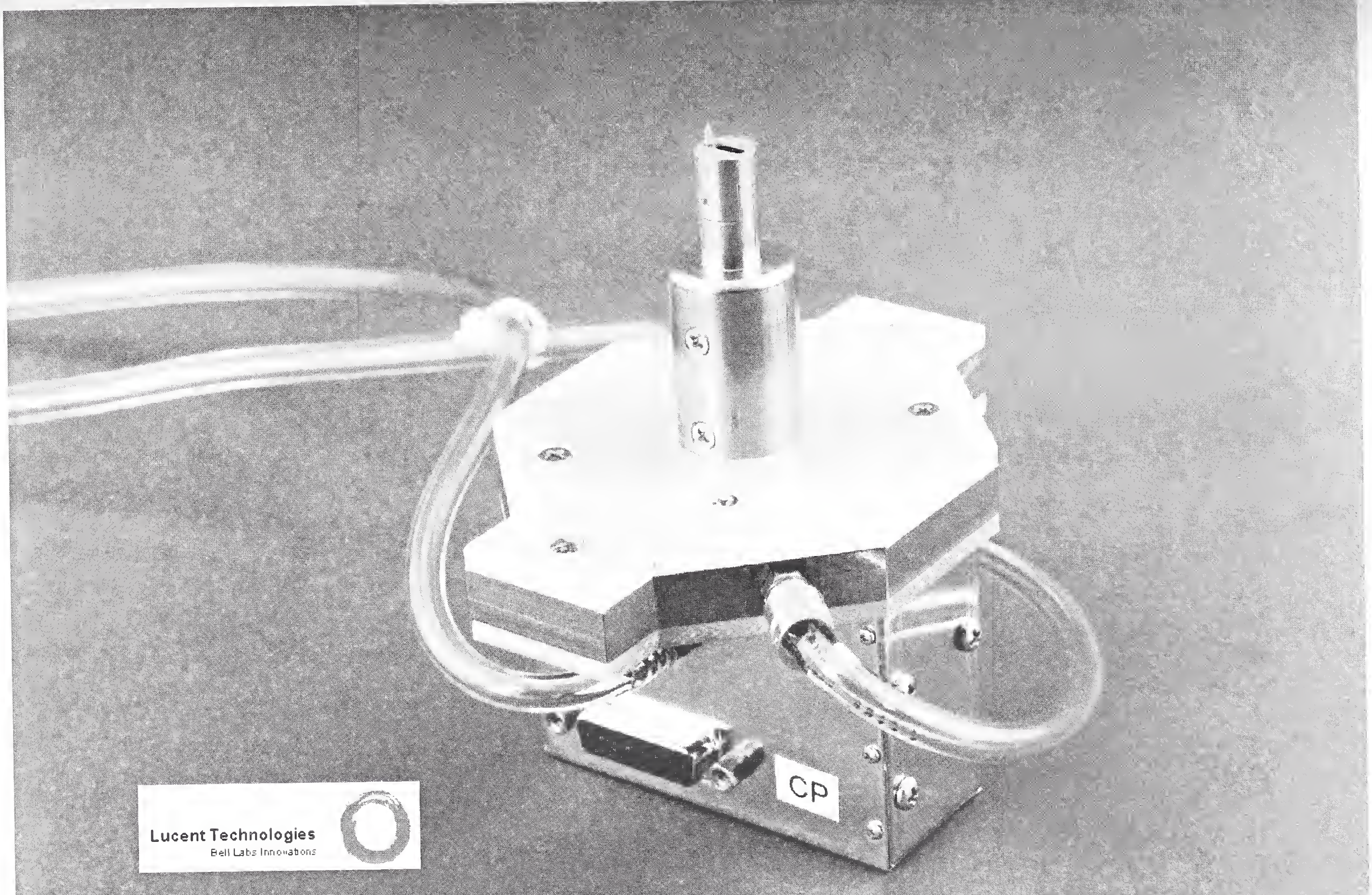
Ripple pyrometer Lucent type PT1 replacement for AST 2800 RTP



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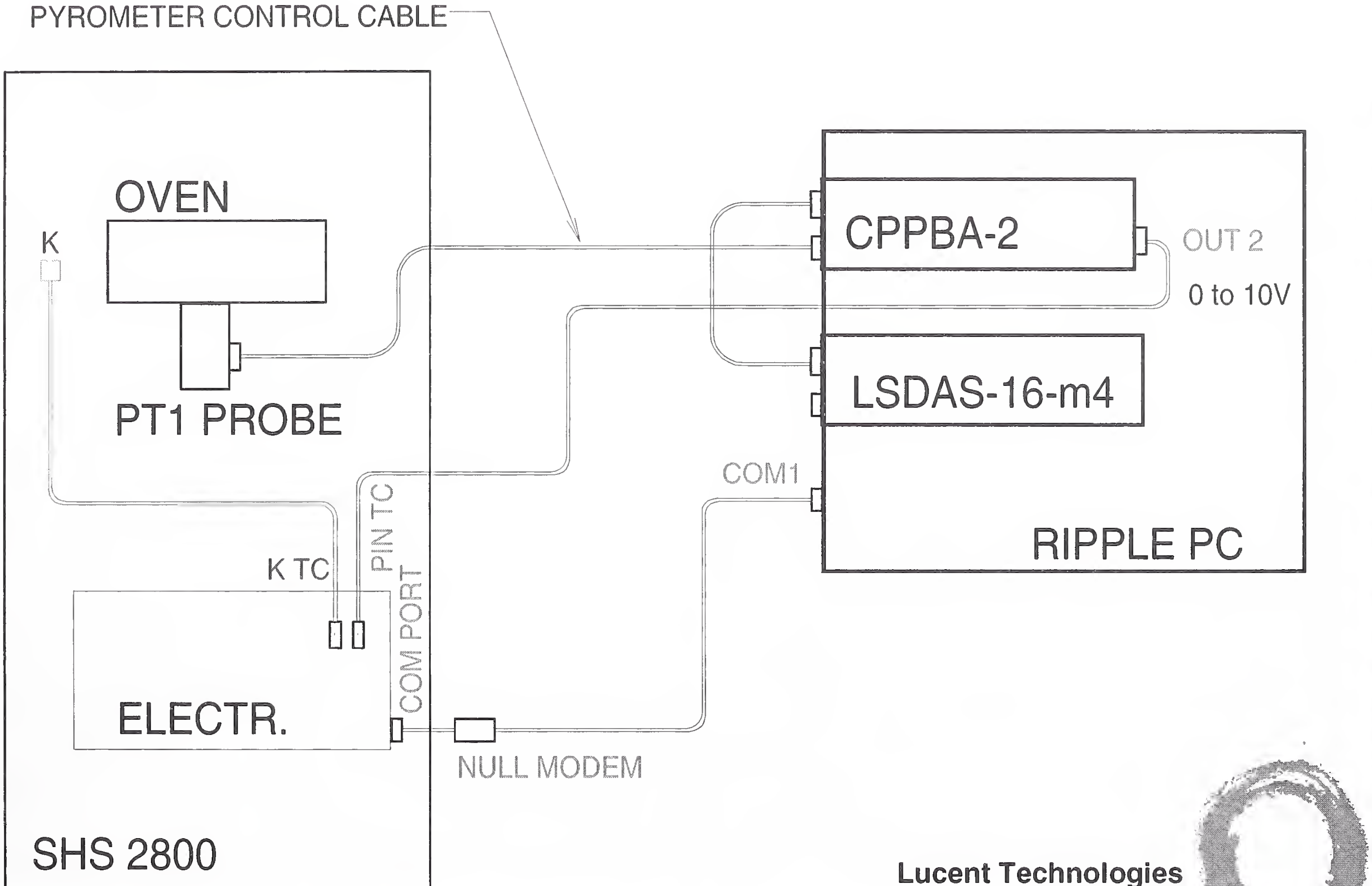
Temperature Profiling of Ripple Pyrometers with Thermocouple Wafers Slide 3

Lucent type PT1 ripple pyrometer

Installation to SHS 2800



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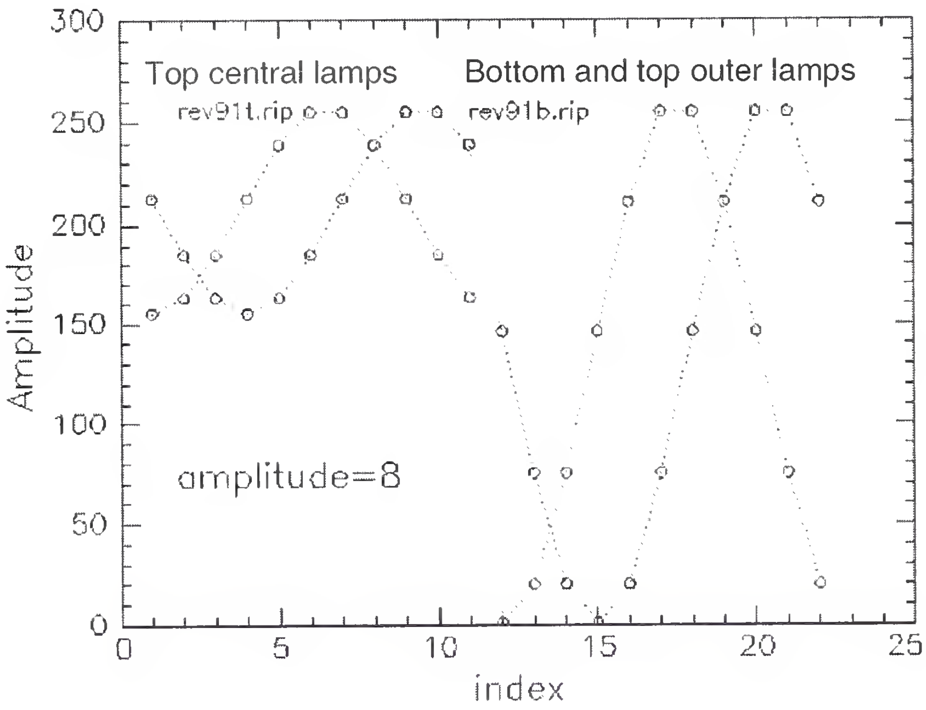
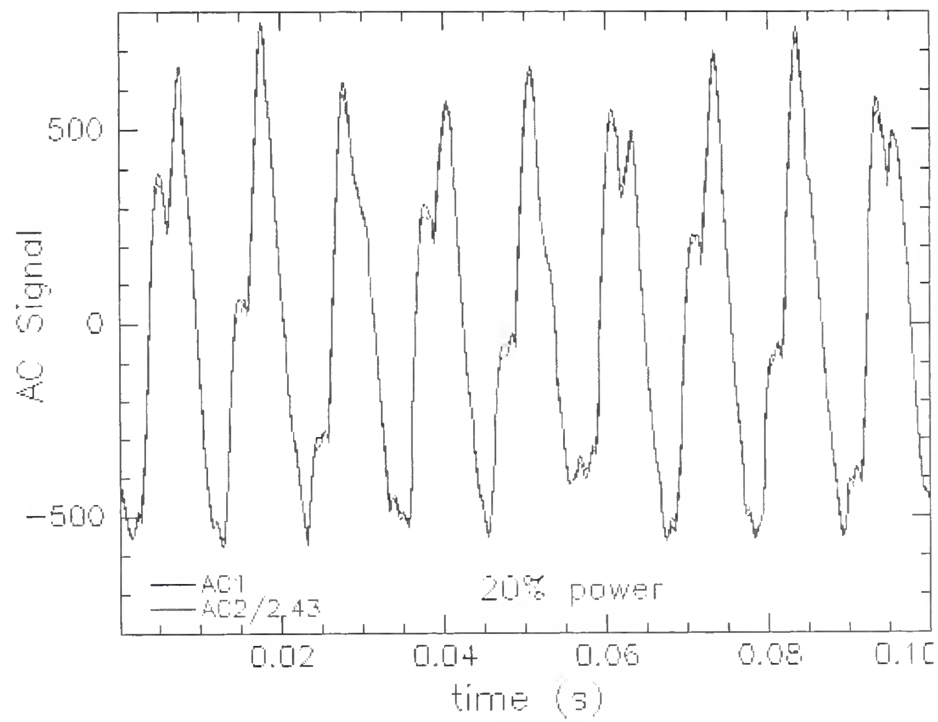
Software controlled ripple modulation at 90.9 Hz

Shape files on AST SHS 2800



AC signals at ripple PC



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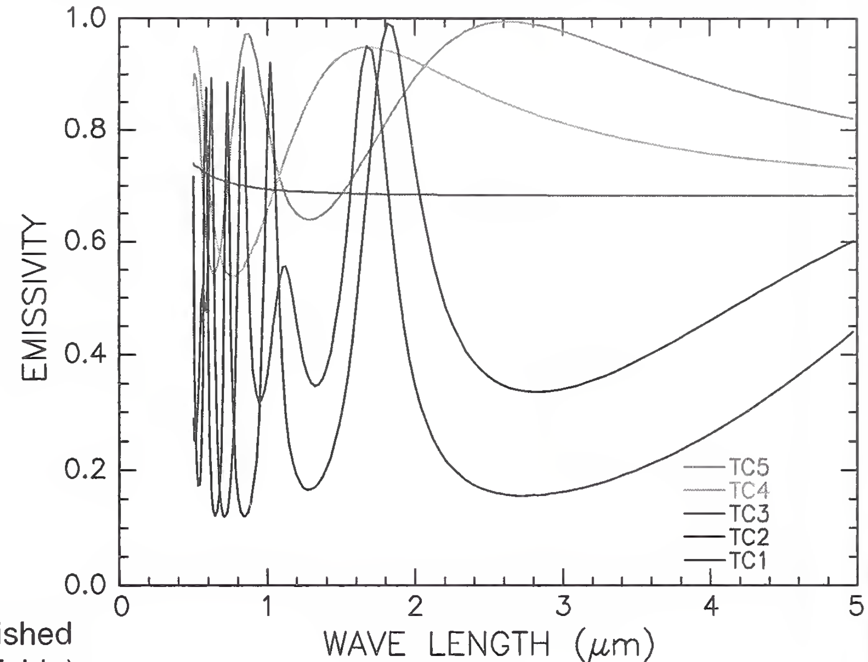
Instrumented Thermocouple Wafers for Temperature Profile

Type ID	Layer 1	Layer 2	Emissivity Range
TC1	400 nm oxide	200 nm poly	low
TC2	150 nm oxide	250 nm poly	medium low
TC3	50 nm oxide	—	neutral
TC4	200 nm oxide	50 nm nitride	medium high
TC5	50 nm oxide	300 nm nitride	high

Layer 1 is back side film adjacent to substrate
Layer 2 is back side surface film
Top side is 5 to 50 nm oxide



↑

Pyrometer filter 2.3 - 2.5 μm

TC Wafer Fabrication

1. Starting material: bulk 0.005 to 0.025 Ω-cm silicon wafers, unpolished back side finish. Inscribe wafer ID type codes on front side (Table).

2. Process wafers with 5 to 50 nm thermal oxide.

3. Process wafer back sides with film layers given in Table. Layer 1 oxide is combination of thermal and CVD-deposited SiO_2; poly is CVD-deposited polycrystalline silicon; nitride is CVD-deposited Si_3N_4.

4. Anneal wafer in RTP, 60 sec at 1050°C.

5. Install type K 0.003" wire size thermocouple junction embedded at center of front side as per SensArray Corp. (Santa Clara) type 1530B or equivalent.

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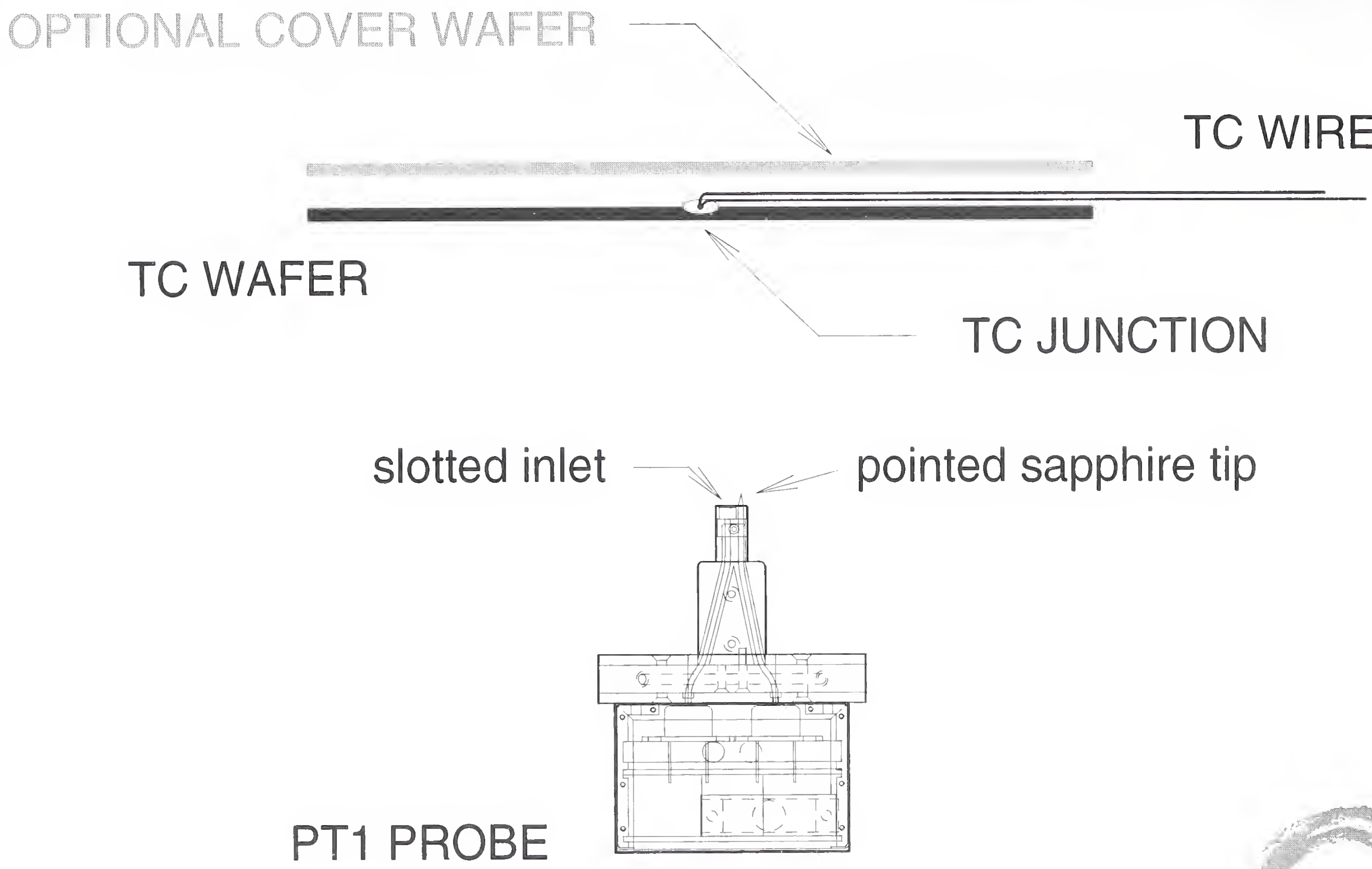
Temperature profile jig



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Temperature profile set up display on ripple pc

at completion with 5 TC wafers

Run screen display with pyrometer settings: sensor_factor, diode … Ffactor TC and ripple data: Ttc, DC1, DC2, AC1, and AC2.

```
PAGE 2   TCSETRP version 2000.01.30 Copyright (c) 2000 Lucent Technologies Inc.
                      DATA ACQUISITION RUN DISPLAY SCREEN
  STATUS    .PRG SAVED           WAFER      Ttc     DC1     DC2     AC1     AC2
      Wafers Counter    5        TC3-2      600.2  0.4407  0.9201  0.0173  0.0624
              Recipe             TC3-2      750.2  0.9906  1.6779  0.0295  0.1039
        Process Step             TC3-2      900.3  1.9506  2.9091  0.0496  0.1731
                Tube             TC3-2     1050.4  3.4076  4.6864  0.0777  0.2686
        Thermocouple             TC4-2      600.2  0.3611  0.8135  0.0073  0.0495
               Pyro              TC4-2      750.2  0.9070  1.5648  0.0129  0.0843
              Pin Tc             TC4-2      900.3  1.8853  2.8107  0.0222  0.1425
          Lamp Power    0        TC5-2     1050.4  3.3910  4.6354  0.0354  0.2235
  Data Capture Timer    0        TC5-2      600.2  0.3343  0.7868  0.0042  0.0463
          Processing    OFF      TC5-2      750.2  0.8812  1.5471  0.0075  0.0789
   SHS Communication    READY    TC5-2      900.3  1.8702  2.8189  0.0134  0.1339
                                 TC5-2     1050.4  3.3977  4.6821  0.0221  0.2095
       Ripple System    READY
  Ripple Temp   Emit    300 0.500
      Ripple DC / AC    0.0000  0.0000  0.0000  0.0000
       sensor_factor    1.31947  1.78293
               diode    0.001305 0 0.0001600 5 0
       base_chck DC     0.00523  0.00510
       base_chck AC     0.00002  0.00002  0.00001  0.00001
          therm_chck    8.43079                               TC5-2
             Ffactor    0.993608                              ↑Wafer ID
KEYS: Pg_Up Pg_Dn access pages  TAB open box  ENTER save entry ESC cancel
```

Analysis screen display: estimated temperature error and emittance range; wafer ID, thermocouple (Ttc) and ripple (Trpl) temperatures, ripple emittance (Emit), net emission signal (Ie), ripple reflection (R), date, time, …

```
PAGE 3   TCSETRP version 2000.01.30 Copyright (c) 2000 Lucent Technologies Inc.
↓ ANALYZED LINES in 30JAN00.TCS  Trpl: +/-  2°C   Emit: 0.176 to 0.879
     Wafer      Ttc    Trpl    Emit     Ie       R       Date      Time  Run line
 X  TC1-2      600.2  600.7  0.1776  0.0524  0.6084  30-JAN-00  9:25   1    1
 X  TC1-2      750.3  749.3  0.1760  0.1473  0.6096  30-JAN-00  9:27   1    2
 X  TC1-2      900.3  900.3  0.1783  0.3285  0.6079  30-JAN-00  9:30   1    3
 X  TC1-2     1050.4 1051.8  0.1850  0.6276  0.6029  30-JAN-00  9:35   1    4
 X  TC2-2      600.2  600.8  0.3452  0.1020  0.4844  30-JAN-00  9:54   2    5
 X  TC2-2      750.2  748.7  0.3436  0.2867  0.4856  30-JAN-00  9:56   2    6
 X  TC2-2      900.3  898.8  0.3462  0.6335  0.4836  30-JAN-00  9:59   2    7
 X  TC2-2     1050.4 1050.5  0.3538  1.1946  0.4780  30-JAN-00 10:03   2    8
 X  TC3-2      600.2  601.8  0.6269  0.1868  0.2760  30-JAN-00 11:25   3    9
 X  TC3-2      750.2  749.1  0.6185  0.5171  0.2822  30-JAN-00 11:27   3   10
 X  TC3-2      900.3  898.2  0.6145  1.1210  0.2852  30-JAN-00 11:30   3   11
 X  TC3-2     1050.4 1050.0  0.6110  2.0590  0.2878  30-JAN-00 11:35   3   12
 X  TC4-2      600.2  603.2  0.8013  0.2415  0.1470  30-JAN-00 11:53   4   13
 X  TC4-2      750.2  750.5  0.7946  0.6701  0.1519  30-JAN-00 11:55   4   14
 X  TC4-2      900.3  899.3  0.7907  1.4500  0.1548  30-JAN-00 11:58   4   15
 X  TC4-2     1050.4 1050.8  0.7869  2.6602  0.1577  30-JAN-00 12:03   4   16
 X  TC5-2      600.2  602.8  0.8790  0.2639  0.0895  30-JAN-00 12:22   5   17
 X  TC5-2      750.2  750.3  0.8715  0.7342  0.0951  30-JAN-00 12:24   5   18
 X  TC5-2      900.3  899.7  0.8655  1.5898  0.0995  30-JAN-00 12:28   5   19
 X  TC5-2     1050.4 1051.3  0.8584  2.9072  0.1048  30-JAN-00 12:32   5   20
 Page 3  X marks lines included in analysis. ↑ ↓ Home End keys scroll table.
KEYS: PG_Up PG_Dn change page  TAB open box  ENTER save entry ESC cancel
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Issues with Using TC's to Calibrate RTP Tools

steag
RTP Systems

Jeff Gelpey
Vice President of Technology
STEAG RTP Systems
San Jose, CA

Workshop on
Temperature Measurement
of Semiconductor Wafers
Using Thermocouples

RTP 2000 Conference
September 19, 2000

1

Issues with TC Measurements on Real Process Tools

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RTP Systems

TC's have traditionally been used to calibrate and check RTP tools, but there are several problems:

- TC Problems
  - Poor quality TC's
  - Poor mounting
  - Response time limitations
  - Changes with temperature cycling
  - Bulk vs. surface mount TC's
- Equipment Problems
  - Difficult to use TC's with rotating wafers
  - TC electronics may not be adequate
  - Procedures do not provide good calibration of radiometer

2

Are TC's the Best Way to Calibrate?

steag RTP Systems

- Is a TC "accurate enough"?
- Is is better to use a process monitor?
  - Can a process monitor be repeatable over time and from site to site?
  - Is there some other calibration technique based on a fundamental physical property (e.g. melting point) that can be practical?
- Should TC's be used to measure uniformity as well as to calibrate radiometers?

3

"Wish List"

steag RTP Systems

- Thin Film TC wafer commercially available (and cheap!) using elemental TCs
  - Withstands hundreds of thermal cycles with no degradation
  - Better than 1 K accuracy over entire temperature range
  - Has option of many junctions to measure uniformity
- Agreement by user community of accuracy, precision and repeatability requirements

4