OCT 1 4 1975

NBS TECHNICAL NOTE 591

A Technique for Measuring the Surface Temperature of Transistors by Means of Fluorescent Phosphor

NATIONAL BUREAU OF STANDARDS

The National Bureau of Standards[1] was established by an act of Congress March 3, 1901. The Bureau's overall goal is to strengthen and advance the Nation's science and technology and facilitate their effective application for public benefit. To this end, the Bureau conducts research and provides: (1) a basis for the Nation's physical measurement system, (2) scientific and technological services for industry and government, (3) a technical basis for equity in trade, and (4) technical services to promote public safety. The Bureau consists of the Institute for Basic Standards, the Institute for Materials Research, the Institute for Applied Technology, the Center for Computer Sciences and Technology, and the Office for Information Programs.

THE INSTITUTE FOR BASIC STANDARDS provides the central basis within the United States of a complete and consistent system of physical measurement; coordinates that system with measurement systems of other nations; and furnishes essential services leading to accurate and uniform physical measurements throughout the Nation's scientific community, industry, and commerce. The Institute consists of a Center for Radiation Research, an Office of Measurement Services and the following divisions:

> Applied Mathematics—Electricity—Heat—Mechanics—Optical Physics—Linac Radiation[2]—Nuclear Radiation[2]—Applied Radiation[2]—Quantum Electronics[3]—Electromagnetics[3]—Time and Frequency[3]—Laboratory Astrophysics[3]—Cryogenics[3].

THE INSTITUTE FOR MATERIALS RESEARCH conducts materials research leading to improved methods of measurement, standards, and data on the properties of well-characterized materials needed by industry, commerce, educational institutions, and Government; provides advisory and research services to other Government agencies; and develops, produces, and distributes standard reference materials. The Institute consists of the Office of Standard Reference Materials and the following divisions:

> Analytical Chemistry—Polymers—Metallurgy—Inorganic Materials—Reactor Radiation—Physical Chemistry.

THE INSTITUTE FOR APPLIED TECHNOLOGY provides technical services to promote the use of available technology and to facilitate technological innovation in industry and Government; cooperates with public and private organizations leading to the development of technological standards (including mandatory safety standards), codes and methods of test; and provides technical advice and services to Government agencies upon request. The Institute also monitors NBS engineering standards activities and provides liaison between NBS and national and international engineering standards bodies. The Institute consists of the following technical divisions and offices:

> Engineering Standards Services—Weights and Measures—Flammable Fabrics—Invention and Innovation—Vehicle Systems Research—Product Evaluation Technology—Building Research—Electronic Technology—Technical Analysis—Measurement Engineering.

THE CENTER FOR COMPUTER SCIENCES AND TECHNOLOGY conducts research and provides technical services designed to aid Government agencies in improving cost effectiveness in the conduct of their programs through the selection, acquisition, and effective utilization of automatic data processing equipment; and serves as the principal focus within the executive branch for the development of Federal standards for automatic data processing equipment, techniques, and computer languages. The Center consists of the following offices and divisions:

> Information Processing Standards—Computer Information—Computer Services—Systems Development—Information Processing Technology.

THE OFFICE FOR INFORMATION PROGRAMS promotes optimum dissemination and accessibility of scientific information generated within NBS and other agencies of the Federal Government; promotes the development of the National Standard Reference Data System and a system of information analysis centers dealing with the broader aspects of the National Measurement System; provides appropriate services to ensure that the NBS staff has optimum accessibility to the scientific information of the world, and directs the public information activities of the Bureau. The Office consists of the following organizational units:

> Office of Standard Reference Data—Office of Technical Information and Publications—Library—Office of Public Information—Office of International Relations.

---

[1] Headquarters and Laboratories at Gaithersburg, Maryland, unless otherwise noted; mailing address Washington, D.C. 20234.
[2] Part of the Center for Radiation Research.
[3] Located at Boulder, Colorado 80302.

NBS ◆ TECHNICAL NOTE 591

A Technique for Measuring the Surface Temperature of Transistors by Means of Fluorescent Phosphor

David J. Brenner

Measurement Engineering Division
Institute for Applied Technology
National Bureau of Standards
Washington, D.C. 20234

CONTENTS

Page

PREFACE

This NBS Technical Note is based on the author's Master's Thesis, "Application of the Phosphor-Ultraviolet Technique to Measurement of the Surface Temperature of Uncapped Power Transistors", which was submitted to the University of Maryland in 1969. The work was performed at, and supported in part by, the National Bureau of Standards. The author wishes to thank Harry A. Schafft of NBS for suggesting the topic, and for assistance in the preparation of this Technical Note. Thanks are also due to John R. Maurey, also at NBS, for use of the microdensitometer employed in the work.

A TECHNIQUE FOR MEASURING THE SURFACE TEMPERATURE OF TRANSISTORS BY MEANS OF FLUORESCENT PHOSPHOR

David J. Brenner

A technique that uses temperature-sensitive phosphor (TSP) to make quantitative measurements of transistor-chip surface temperatures over the range of 170 - 210°C is described. The experimental procedure consisted of depositing a thin coating of phosphor on uncapped power transistors, and then photographing the visible fluorescence generated under near-ultraviolet (uv) excitation. The cooler regions produced a brighter fluorescence than the hotter areas. The surface temperatures of operating transistors were determined by comparing, on a point-by-point basis, the photographic density of operating photographs to the density of a family of calibration photographs. Repeated temperature measurements always fell within a 4°C overall error range when the phospor surface was scanned with a 25 x 25 μm aperture. The error band dropped to less than 2°C when a 50 x 50 μm aperture was used. Coarseness of the phosphor coating seemed to limit spacial resolution to about 20 μm. Any narrow temperature range between 20 and 400°C can probably be measured by selecting a suitable level of uv irradiation and/or a suitable phosphor.

Key words: Surface temperature; temperature measurement; temperature-sensitive phosphor; thermographic phosphor; transistor-chip temperature.

1. INTRODUCTION

1.1. Purpose

The suitability of temperature-sensitive phosphor (TSP) for making quantitative temperature measurements has not been reported in the literature. It is the purpose of this report to provide information on this subject. In particular, the use of TSP in making quantitative measurements of the surface temperature of power transistors operating under steady-state (dc) conditions is described. Emphasis is placed on describing the experimental techniques, defining the limitations of the apparatus, and determining the reproducibility of the temperature measurements obtained. Although papers by Blanks [1] and Goryunov, Ovechkin, Tolkacheva, and Feoktistov [2] describe the use of TSP to obtain temperature measurements on transistor chips, neither paper stated the measurement accuracy obtained.

1.2. The Need for Temperature Measurement

Most of the heat developed by a transistor is produced in its collector junction, where the highest temperature is found. In power transistors it is common for the collector current to be distributed unevenly over the area of the collector junction [3], thus causing nonuniform heating of the junction and local hot spots.

Hot-spot temperature is an important parameter because it strongly influences transistor life expectancy [4]. Measurement of the collector-junction temperature profile provides information that is very important for reliability studies, the design of transistor structures, and determining temperatures produced by actual circuit conditions.

Since the collector junction is buried within the silicon chip that forms the transistor, its temperature cannot be measured directly. An indirect measurement technique that is frequently employed is the utilization of a temperature-sensitive electrical parameter of the transistor as a temperature sensor [5]. This approach is very convenient because the electrical parameters can be measured at the terminals

of encapsulated transistor chips. However, the temperature-sensitive parameter technique is not satisfactory if local hot spots are present[1] because averaging of the parameter over the whole junction area results in underestimating the hot spot temperature [3]. When non-uniform heating occurs, collector junction temperatures can be measured only on a transistor whose junction is close to the surface of the silicon chip; it being assumed that the chip surface temperature, which can be measured, will closely approximate the junction temperature. Whether or not this is true is a judgment that must be made individually for each transistor tested. This report does not attempt to resolve the problem.

1.3. Techniques for Measurement of Surface Temperature

Infrared Microradiometer. Quantitative surface-temperature measurements on transistors can be made with an infrared microradiometer (IRM). An IRM measures temperature on a point-by-point basis, with a spot size diameter in the order of 25 μm. Basically the technique employs a microscope designed for use in the infrared, and a detector which measures the infrared power reaching the microscope "eyepiece." The temperature indication is an electric signal and can be read on a meter, recorder, or other instrument. What the IRM actually measures is the infrared radiance[2] of the surface under test. It is necessary

---

[1] When operated at collector-to-base voltages above about 20 V, transistors are likely to develop one or more hot spots. A large increase in the junction-to-case thermal resistance occurs at the hot spot. Thermal resistance measurements made using the temperature-sensitive parameter technique will show the increase in thermal resistance qualitatively and can be used as a test for the onset of hot spots.

[2] Radiance describes the strength of radiation emitted from a surface, and is defined to be the power emitted per unit solid angle per unit area. For example, radiance can be expressed as $(w/sr)/cm^2$, where sr means steradian.
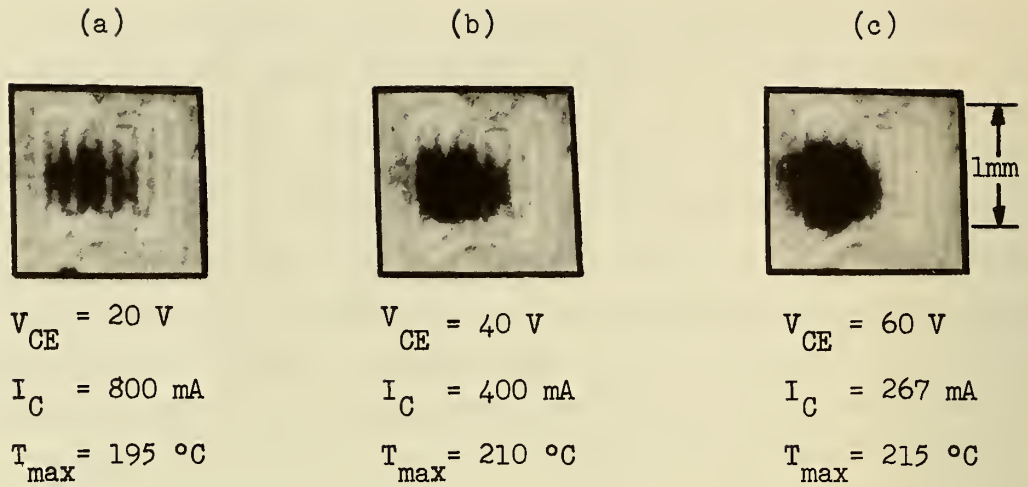
to paint the transistor surface with an opaque coating if accurate measurements are to be obtained. This is required because silicon and silicon dioxide transmit infrared and thereby allow radiation (in particular, recombination radiation) that originates within the transistor to be detected by the IRM [4]. The opaque coating also provides a surface of uniform and reproducible emissivity. At the present time the IRM is the only commercially available instrument that can make quantitative measurements of transistor surface temperature. Although the IRM can provide good accuracy and spacial resolution, its cost and complexity place it out of reach of many who have need of its capabilities.

Liquid Crystals. A relatively simple and inexpensive technique sometimes used for surface temperature measurement employs liquid crystals [6]. These are organic materials which maintain a fair amount of molecular order when in the liquid state. The ordered molecules of some liquid crystals can function as an optical grating whose internal spacing is a function of temperature and can produce temperature-dependent, reversible color changes. The colors are produced by selective reflection of the spectral components of white light. To measure surface temperature, the surface is coated with a thin layer of a suitable liquid crystal and then illuminated obliquely by a beam of white light. If the eye of the observer is maintained at an appropriate position, then the color seen will depend on the temperature of the liquid crystal. In order to prevent reflection of unwanted light from the substrate surface, it is usually necessary to blacken the substrate before it is coated with the liquid crystal. Although liquid crystals for thermographic work are available for temperatures from $0^{o}C$ to at least $230^{o}C$, whether they can provide quantitative measurements at the higher temperatures has not been reported in the literature.

Temperature-Sensitive Phosphor. Another relatively simple and inexpensive method of making surface temperature measurements is provided by temperature-sensitive phosphors (TSP). The use of phosphors in making temperature measurements originated with work done by Urback, Nail, and Pearlman [7] in the 1940's. In the succeeding years, improved phosphors and a variety of procedures for applying the phosphor to the

4

surface under test have been achieved [8]. This technique employs phosphors which exhibit a strongly temperature-dependent fluorescence during irradiation by near-ultraviolet (uv) light. Good temperature sensitivity in a desired temperature range is achieved by selecting a suitable combination of phosphor and uv intensity. In its simplest form the technique consists of coating a surface with a thin layer of phosphor and then observing the visible fluorescent pattern that is produced under uv irradiation. This arrangement suffices to obtain a qualitative picture of the temperature profile, which is sometimes all that is needed, as when only location or size of a hot spot is of interest (see photographs in figure 1). If the test conditions are carefully controlled, then the radiance of the phosphor fluorescence can provide quantitative temperature measurements. The remainder of this report describes the use of TSP in making quantitative temperature measurements.

| (a) | (b) | (c) |

V_{CE} = 20 V V_{CE} = 40 V V_{CE} = 60 V

I_C = 800 mA I_C = 400 mA I_C = 267 mA

T_{max} = 195 °C T_{max} = 210 °C T_{max} = 215 °C

1mm

All photographs are 16X enlargements of the same 2N3767 silicon power transistor dissipating 16 watts. The transistor is mounted on a heat-sink held at 40 °C.

Figure 1.   TRANSISTOR HOT SPOTS. This family of photographs shows how hot spots are displayed by a phosphor-coated transistor chip. The photographs show the fluorescent pattern produced under uv illumination. The location, size, and relative temperature of the hot spots (dark region on photographs) are obvious. Note that the hot spot temperature increases as the collector-to-emitter voltage of the transistor is increased, even though the total power dissipation is held constant. This effect was seen in all transistors tested.

A. vacuum photodiode
B. aluminum housing
C. uv-lamp bulb
D. uv-transmitting filter

E. bakelite thermal insulator
F. ground-glass diffuser
G. plain-glass diagonal
H. light stop

I. TUT
J. heat sink
K. vacuum gauge
L. film

M. 35-mm camera body
N. extension tube
O. focusing lens
P. uv-absorbing filter

Q. uv-light absorber
R. small plain-glass diagonal
S. optical window
T. channel for cooling fluid

U. resistance heater
V. thermocouple
W. vacuum chamber
X. outlet to vacuum pump
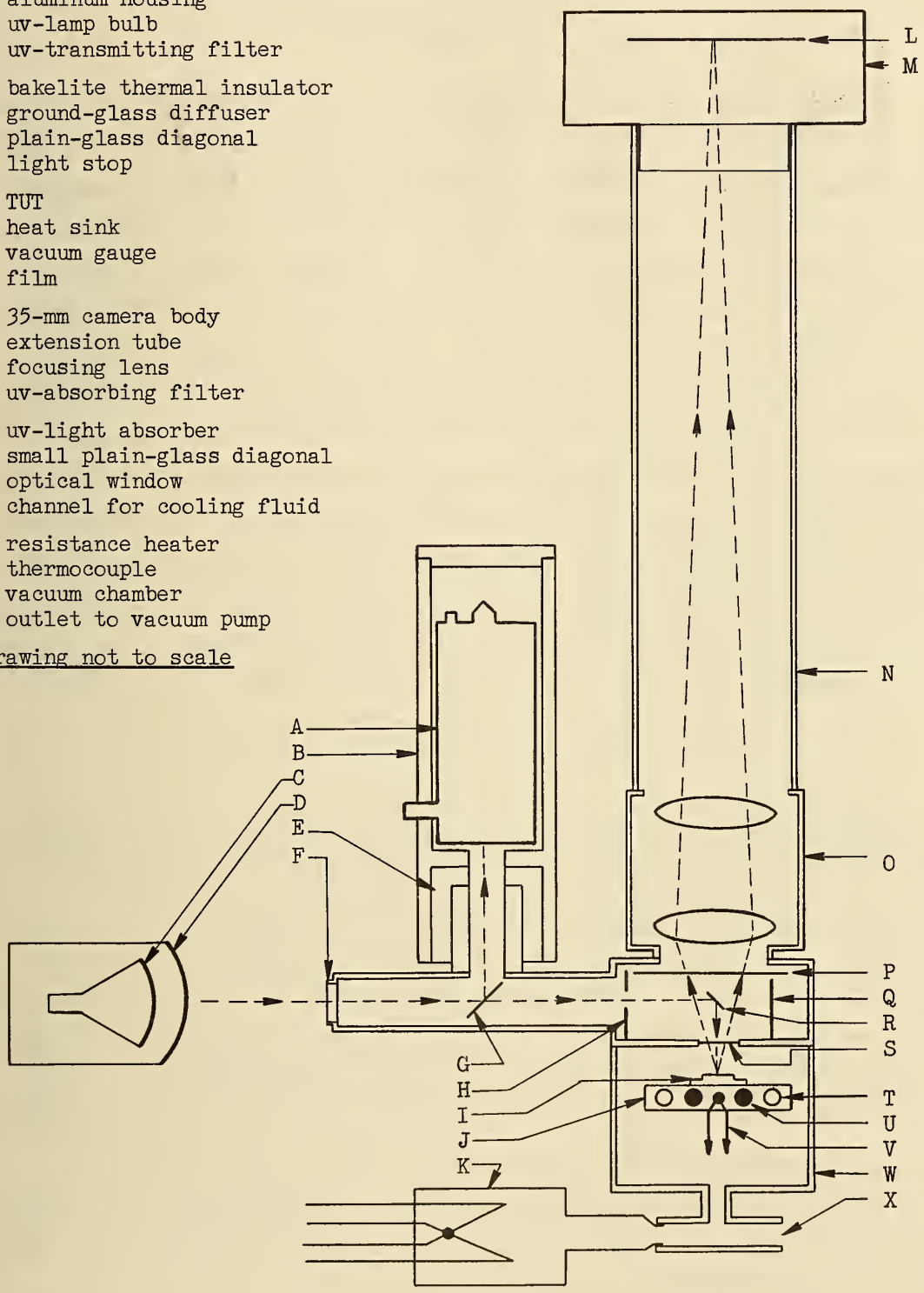
   drawing not to scale

Figure 2. DIAGRAM OF APPARATUS.

7

2. DISCUSSION OF EXPERIMENT

2.1. Experiment Outline

A brief description of the experiment will provide a framework
for presenting the material in this section. The silicon chip of the
transistor under test (TUT) was coated with a thin layer of phosphor
and then mounted on a temperature-controlled heat sink. Light from a
uv lamp was reflected down onto the TUT by a small glass diagonal and
caused the phosphor coating on the TUT to produce a green fluorescence.
The fluorescent light passed upward, through a uv-absorbing filter and
a lens, to a photosensitive film. An 8X enlargement of the phosphor
coating was recorded by the film. After development the film was
analyzed with a microdensitometer to extract the temperature data. In
order to obtain quantitative temperature measurements the variables of
the measuring system, such as uv intensity and film development, were
defined and maintained constant throughout the course of the experiments.
The reproducibility obtained when measurements were repeated was used
as the criterion for judging performance of the TSP.

2.2. Mechanical and Electrical Design

Figure 2 shows the experimental apparatus used. A heat sink (J),
made from a 3/8" thick copper plate, accommodates a chromel-alumel
thermocouple (V), resistance heaters (U), and channels (T) for a cool-
ing fluid. The thermocouple is soldered to the bottom of a narrow,
1/4" deep hole drilled in the plate, and is located under the geometric
center of the case of the TUT. It should be noted, however, that the
transistor chip is not necessarily located at the center of its case.
The heating elements enable the heat sink to serve as a hot plate for
use in calibrating phosphor radiance as a function of temperature.

A cooling fluid, either water or air, is contained by 5-mm out-
side diameter glass tubes that pass through the heat sink and the wall
of the vacuum chamber (W). These two tubes also provide the mechanical
support for the heat sink. In order to ensure a good thermal path
between the glass tubing and the heat sink, the outside of the tubes

was ground to produce a snug fit[3] in the heat sink. A coating of thermally conductive, zinc-oxide loaded, silicone grease was used to further improve the thermal contact. The steps taken to provide good thermal contact are important because the heat transfer ordinarily provided by air is not available when the chamber is evacuated. With a water flow of 5 cm^3/s, the thermal resistance between heat sink and coolant was about $1.7^{\circ}C/W$. This is close to the thermal resistance calculated for the wall of the glass tube alone and is not affected by vacuum conditions. The glass tubes pass through oversize holes in the wall of the vacuum chamber, and vacuum sealing is achieved with silicone rubber to allow movement of the tubes as the heat sink changes dimensions.

Heat-conducting grease was also used between the heat sink and TUT. It was necessary to remove the excess grease which squeezed out as the TUT was bolted to the heat sink. Otherwise, volatile components of the grease were found to evaporate at elevated temperatures and condense on the optical window (S) of the vacuum chamber. Power resistors having axial leads were used for the heaters. (Their ceramic bodies were out-of-round and were not altered.) Installation consisted of coating the resistors with a water-base ceramic cement and then, before the cement dried, inserting them into holes drilled in the heat sink. This construction did not result in good thermal contact between heater sink in vacuum; consequently, the heaters ran much hotter than the heat sink. In fact, if the heaters were maintaining the heat sink at a fixed elevated temperature under vacuum, then quickly releasing the vacuum would cause the temperature of the heat sink to increase several degrees.

The vacuum chamber was evacuated by a mechanical vacuum pump. A pressure of less than 0.1 mm Hg was maintained during the operation of

---

[3]The process of grinding to the required diameter also improved the roundness of the glass tubing. Before grinding, its outer surface was about 1% out-of-round.

the equipment and was continuously monitored by a thermocouple vacuum gauge (K). This modest vacuum was sufficient to provide thermal insulation and protect the transistor and heat sink from excessive oxidation at elevated temperatures. The collector-to-base leakage current of some transistors was observed to permanently increase severalfold when the silicon chip was heated in air.

The electronic equipment used in the experiment is conventional in its design. One or more regulated power supplies, which were manually set to the voltage desired, provided the collector-to-emitter voltage for the TUT.

The voltage was measured by a potentiometer having an error of less than ±0.5% and reproducibility to within ±0.2%. The desired collector current was also set manually, and a servo amplifier maintained this value by adjusting the base drive to the TUT. A null type of circuit measured the collector current with an error of less than ±0.6% and reproducibility to within ±0.2%. A current-limiting resistor was placed in series with the collector of the TUT to protect the equipment in the event that the TUT broke down. Sometimes the TUT was also saved. The collector-to-emitter voltage was monitored by an oscilloscope to check for oscillation. Some of the transistors tested did oscillate at about 1 MHz in the test circuit used, but the connection of a 10 nF capacitor between the collector and emitter terminals stopped the oscillation.

A servo control that governed the power applied to the heaters maintained the heat sink at any desired temperature between 20°C and 246°C. The heat-sink thermocouple, whose reference junction was in an ice bath, provided the control signal. Heat-sink temperature was known to within $\pm 2^{\circ}$C of its true value, and was believed to be reproducible to within a 0.5°C overall range. The intensity of the uv lamp (C) was stabilized by a servo control that used a vacuum photodiode (A) to monitor the uv. Film exposure time was measured by an electric stopclock that was actuated by the flashbulb contact in the camera body (M).

2.3. Transistors Tested

Any power transistor that has the semiconductor surface unobscured (as by connecting wires, heavy metallization, etc.) is a satisfactory test object. Three medium-power transistor types, the 2N3739, 2N3741, and 2N3767 were chosen for experimentation. The transistors are rated to dissipate either 20 W or 25 W when their case temperature is 25°C, and to operate with junction temperatures up to 175°C or 200°C. The higher ratings apply to the 2N3741. Junction temperatures well above these values were frequently produced during the experiments and usually did not noticeably degrade the transistors.

All of the transistors tested came packaged in TO-66 (small diamond shape) cases. In order to reach the silicon chip, either a lathe or a small saw was used to carefully cut off the cap of the transistor case. The active portion of each transistor was a square silicon chip approximately 1.5 mm on an edge, and whose surface was composed of silicon dioxide and aluminum. A protective coating of silicone varnish or silicone rubber was frequently found on top of the chip and required removal before a phosphor layer could be deposited. The aluminum metallization on the emitter and base fingers of the chip was soft and was sometimes scratched and damaged during the removal of the protective coating. Also, the wires that connected the emitter and base regions to the header terminals were sometimes broken by handling. These were thin, soft aluminum wires, and the strength of the bonds at the wire ends was low. A minor problem encountered was that the transistor chips were randomly located on their headers, thus making it necessary to provide a means of bringing the off-center chips into the field of view of the camera. The maximum placement difference observed was approximately 2 mm overall. Adjustment was made by sliding the vacuum chamber (W) on its upper lid, as required.

Several transistor types were found that were quite rugged mechanically, but these were discovered too late to be employed in this project. Two such types were the 2N3583 and 2N3878. The main advantage of these transistors was that the aluminum metallization on the silicon

11

chip was protected from mechanical damage by a hard, glassy layer of aluminum oxide. Another advantage was that the electrical conductors joining the chip to the header terminals were sturdy and firmly anchored at both ends.

### 2.4. Deposition of the Phosphor Coating

The thickness chosen for the phosphor coating is determined by the requirements of the temperature measurement. A uniform, single layer (monolayer) of phosphor grains provides the best measurement of detailed temperature profiles. Because the transistors under test might develop very small hot spots, a monolayer coating is desirable. It is difficult to produce a good monolayer coating, however, and a thin coating is also somewhat transparent (fig. 3). This transparency causes the brightness of the coating fluorescence to be influenced not only by temperature, but also by the reflectivity of the surface coated and by variations in coating thickness. An advantage of transparency is that the substrate surface detail serves as a map upon which the temperature profile will be superimposed. Thick coatings, on the other hand, are opaque, fluoresence more brightly, and may be easier to produce. But the thick coating is not able to display the finer details of the temperature profile, if there happen to be any. Coatings 40 μm or more in thickness can probably be considered opaque.

There are several ways that a thin layer of phosphor can be deposited on a transistor chip. One method is to form a suspension of phosphor particles in a liquid and let the phosphor settle out onto the chip surface. The choice of liquid is quite broad: Ethyl alcohol is frequently used; water has the advantage of holding the phosphor in suspension for a longer time; lacquer or other adhesive vehicle can be used if a permanent coating is desired; and Blanks [1] claims to have obtained near-continuous coatings about 13 μm thick using a silicone varnish. Electrostatic deposition techniques might also be usable.
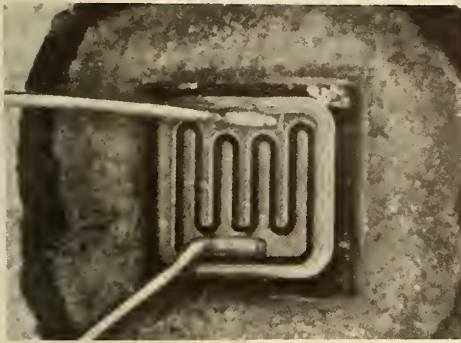
a) 2N3767 transistor chip. These transistors had bare aluminum metallization.
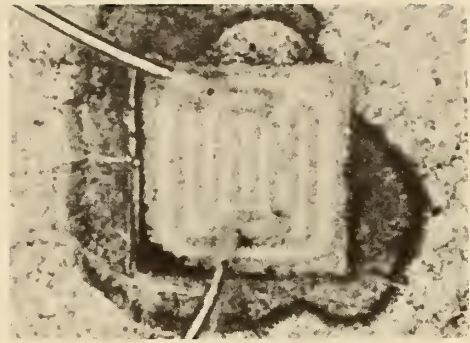
b) Transistor chip, similar to that at left, but with thin phosphor coating. Note that metallization pattern is visible through the coating.

c) 2N3878 transistor chip. These transistors had the aluminum metallization covered by a layer of aluminum oxide.

d) Transistor chip, similar to that at left, but with thin phosphor coating. Note that metallization pattern is not easily seen thru the phosphor coating.

Figure 3. VISIBILITY OF TRANSISTOR SURFACE THRU PHOSPHOR COATING. The photographs were taken at room temperature with diffuse white light illumination. Compare with figure 5a and 5b, which shows the appearance of the phosphor coating under low-angle, grazing illumination.

A floatation technique was used to form the phosphor[4,5] coatings for this project. A thin, floating phosphor layer was first formed on water, and then transferred to the transistor chips. The phosphor was supported by the surface tension "skin" of the water. None of the other liquids that were tried could support the phosphor. Surface tension effects were also used to compact the phosphor granules into a close-knit layer that resisted break-up and thus was easy to work with.

A sketch of the apparatus used to phosphor-coat the transistor chip is shown in figure 4. A tall metal tube was placed upright on the rim of a dish of water. Inside the tube were a phosphor reservoir and an air jet. Puffs of air from the jet lifted the phosphor particles out of the reservoir and allowed them to fall onto the water. Although most of the phosphor sank to the bottom, useless, some did float on the surface of the water. After a thin layer of phosphor was deposited over most of the water, the metal tube was removed from the rim of the dish. Under 45X magnification the coating appeared to consist of a monolayer along with a number of small clusters of phosphor particles. The excess phosphor that formed the clusters was removed by directing a gentle stream of air across the surface. When evaporation of the water was prevented, the floating layer could be stored for many weeks.

The surface-tension force of the water was used to compact the phosphor particles. This was accomplished by introducing a small amount of oil at the edge of the water, causing the phosphor particles to be driven together. Several oils were tried before a satisfactory

[4]Radelin Thermographic Phosphor #2090 was used. It is one of a series of four phosphors, covering the range from room temperature to $400^{\circ}C$, that is available from the United States Radium Company, Morristown, New Jersey. These are the only phosphors known to the author which are manufactured for the express purpose of making temperature measurements.

[5]Commercial products are identified in this paper in order to adequately describe the experiment. In no case does such identification imply recommendation or endorsement by the National Bureau of Standards, nor does it imply that the products identified are necessarily the best available for the purpose.

to 15 psi air supply

brass cylinder

air jet, 0.35 mm ID

phosphor

floating layer of phosphor

crystallizing dish
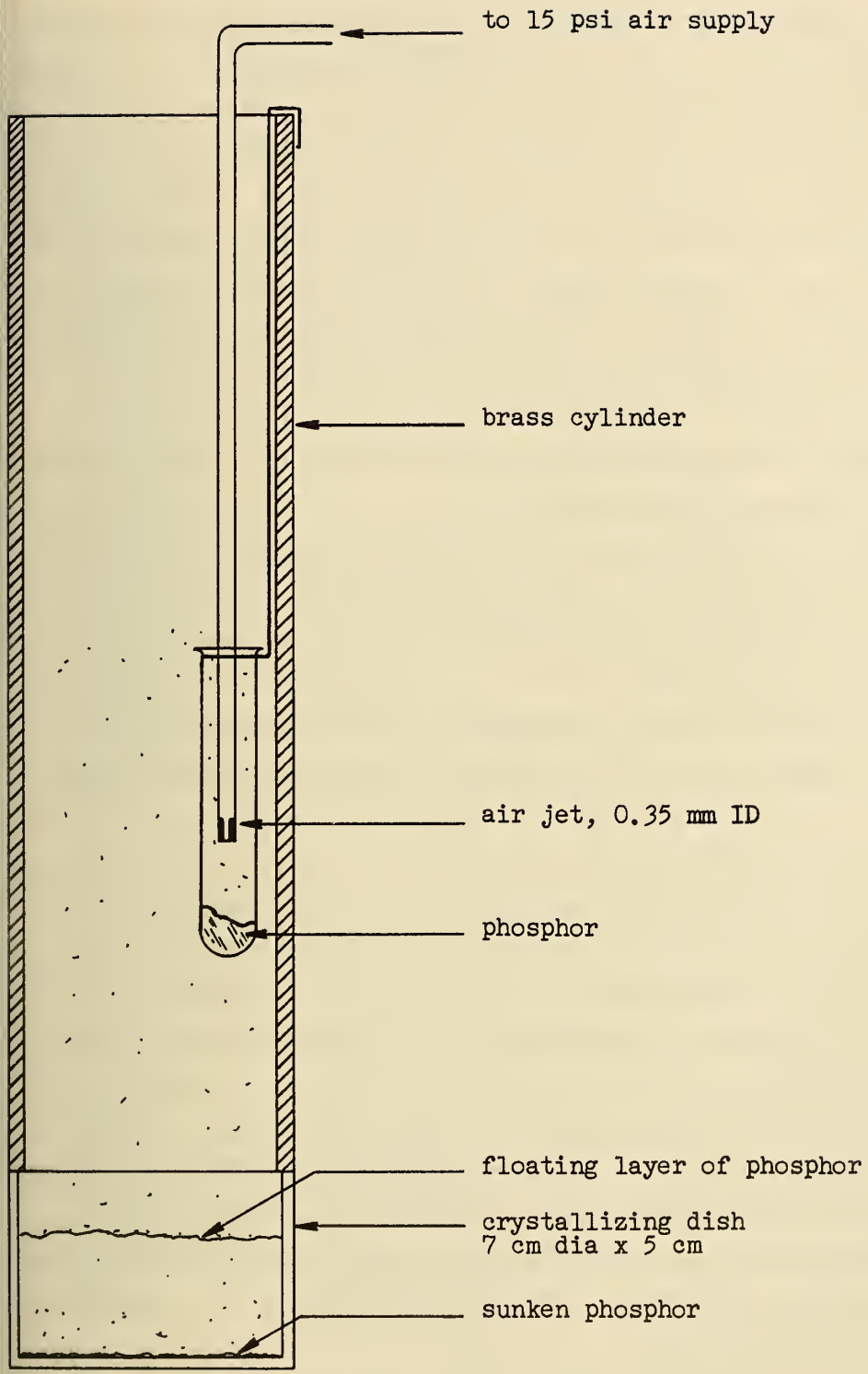7 cm dia x 5 cm

sunken phosphor

Figure 4.   APPARATUS USED TO PRODUCE THIN PHOSPHOR COATINGS.

one was found. Some, such as general purpose lubricating oils, were too vigorous and caused the phosphor particles to be driven upon one another, thereby increasing the coating thickness. While in contrast to this, the type of oil that is used in mechanical vacuum pumps produced almost no compaction (this oil spread out very slowly on water). As it turned out, the residual oils remaining on recently washed hands gave the best results and produced admirable compaction of the phosphor, although this may not work for everyone. Simply dipping a finger into the water for a moment would usually compact the phosphor quite nicely. Prior to the compaction, however, the water had to be free of oil and other surface-tension reducing materials; otherwise the surface tension would be too weak to produce adequate compaction.

The floating phosphor layer could be easily transferred to surfaces that were easily wet by water. Satisfactory phosphor coatings could not be deposited on water-repellent surfaces because the water rolled off the surface, carrying the phosphor with it. Good coatings could sometimes be obtained on surfaces having intermediate wettability characteristics. Learning how to make the silicon transistor chips wettable was a major problem.

Although a few chips were easily wet by water as received, most were covered by a water-repellent coating, of which several types were encountered. It was found that some of these coatings could be softened and removed with the aid of solvents such as methylene chloride, paint remover, or commercial preparations such as those used for chemically removing the enamel insulation from magnet wire. Frequently it was necessary to use mechanical means to remove the softened coating, sometimes resulting in damage to the transistor. The 2N3739 transistors were occasionally coated with a blob of white silicone rubber, but commercial preparations are available which easily dissolve this. Once the water-repellent coating was removed, final cleaning with detergent and water was sometimes found to be helpful.

After a satisfactory floating phosphor layer was obtained, the transistor was lowered into the water at a phosphor-free region. (Phosphor must not be allowed to adhere to the silicon chip in this

step.) The very thin oil film on the surface of the water did not cause trouble. The transistor was then oriented so that the chip faced upward, and slowly lifted up through the phosphor layer and out of the water. As the transistor was withdrawn from the water, it picked up a single-layer coating of phosphor that adhered tenaciously. But if the rim of the transistor case happened to trap a pool of water, then the phosphor layer would float on top. When this happened, the phosphor layer was floated down to the chip by removing the water with absorbent paper. The transistor was then set aside to dry. Drying time was just a few minutes if the transistor was heated slightly. The short drying time was one of the advantages of the floatation method. By way of comparison, a coating deposited from a liquid suspension had to be left undisturbed until the liquid evaporated naturally, usually several hours. Attempts to hasten the drying, such as by mechanically removing excess water or by heating, usually produced convection currents that ruined the coating.

The dry phosphor coating withstood careful handling quite well, but sharp jolts and strong air currents had to be avoided. The phosphor could be easily removed with a soft brush or a water spray. Because the phosphor always covered much more than just the silicon chip, it was removed from areas whose temperature was not of interest - - the excess phosphor was a source of potentially interfering light that could increase the error of the temperature measurements.

The average diameter of the individual phosphor grains is 9μm. When deposited on the silicon dioxide or aluminum oxide regions of a transistor chip, the phosphor grains produced a coating that roughly approximated a monolayer, but some clumps of phosphor grains were also present (fig. 5). The height of the clumps was usually less than 30μm. On bare aluminum metallization a much higher proportion of phosphor clumps were produced and the clump size was larger, ranging up to about 50 μm in diameter.
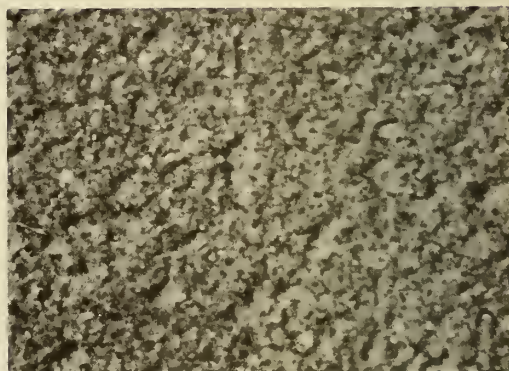
a) Phosphor-coated transistor
(similar to that shown in
Fig. 3b) illuminated by
low-angle, grazing light
to emphasize the texture
of the phosphor coating.
15X
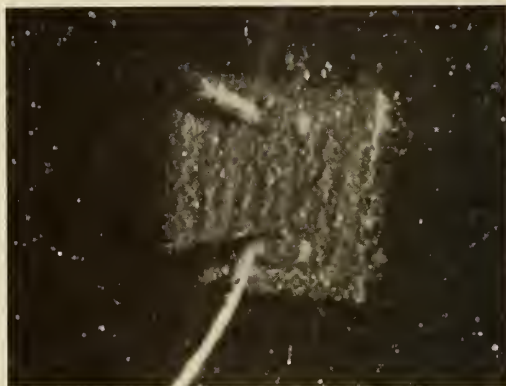
b) Thin phosphor coating (on
a black anodized aluminum
plate) similar to that in
a, above. Diffuse, white
light illumination used.
40X

c) Thin phosphor coating (on
a plain silicon chip)
similar to a, above. This
photograph was made by a
scanning electron microscope
and was supplied by the NBS
Electronic Technology Division.
Optical microscopes do not have
sufficient depth-of-field at
high magnification to show in
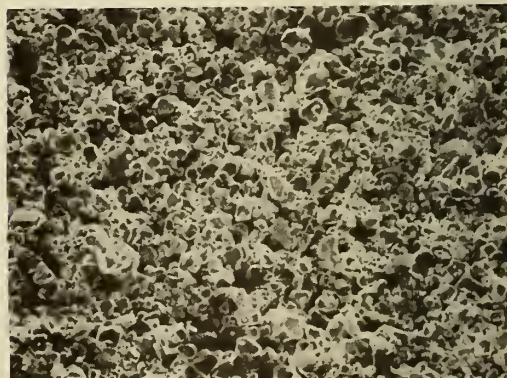focus an entire phosphor grain.
205X

Figure 5. TEXTURE OF THIN PHOSPHOR COATING. Phosphor is at room
temperature.

2.5. Ultraviolet Lamp Characteristics

The uv light source was a 100-watt high-pressure mercury arc bulb (C) having an internal spotlight reflector. This type of bulb emits light over a wide spectral range which includes the uv, visible, and infrared regions. Since the uv light was used to generate a weak, green fluorescence, it was necessary to remove all competing light from the uv beam. A uv transmitting filter (D), which was supplied as part of the uv lamp, absorbed most of the visible light emitted by the bulb. Measurement of the lamp's (including its filter) spectral output revealed very strong radiation of the 366-nm (uv) line of mercury, a small amount of violet light (probably near 405 nm), and a continuum that began at about 680 nm (deep red) and extended into the infrared. The continuum was probably ordinary heat radiation from the hot bulb. The red and the violet radiation was visible to the eye.

The mercury-arc bulb was energized by 60-Hz alternating current. Because the uv light intensity is able to follow the cyclic variation of the current, its intensity varied with time like a full-wave rectified 60-Hz sine wave. Whenever this report mentions the intensity of the uv light, it is the simple average value that is meant unless specifically stated to the contrary.

Short term drift of the uv intensity, after warmup and with constant voltage, was roughly 1% per minute. The intensity changes commonly occurred in jumps of about this magnitude and frequency. Occasionally, and for no apparent reason, the lamp stability was much better than this. A lamp operated from a dc power source would probably have better stability.

2.6. Ultraviolet-Light Monitor

The ground-glass diffuser (F) that the uv light encounters at the entrance to the test apparatus was empirically found to be necessary to obtain a meaningful indication from the vacuum photodiode. With the ground glass removed it was observed that various positions of the uv

19

lamp which produced an identical output current from the photodiode, did not necessarily produce identical uv intensity at the phosphor surface. The ground glass greatly reduced this ambiguity.

After passing through the ground glass, the uv light came to a glass diagonal (G) that reflected about 10% of the light up to the photodiode. In order to prevent the hot heat sink in the vacuum chamber from affecting the photodiode sensitivity, the photodiode was mounted in an aluminum housing that was thermally insulated from the supporting structure. The vacuum photodiode has an S-11 spectral response and exhibits good temporal stability. The S-11 response has peak sensitivity at about 420 nm, and approximately an 80% response at 366 nm. Its sensitivity to red and infrared light is low.

The photodiode and the servo control associated with the uv lamp acted to stabilize the average value of uv intensity. It should be mentioned, however, that the radiance of the phosphor fluorescence is a non-linear function of the incident uv intensity (see Section 3.3), so holding the average value of the uv intensity fixed does not guarantee that the time-averaged fluorescent brightness remains constant. For example, the brightness of the phosphor fluorescence would probably be slightly weaker if the uv lamp were energized by a dc rather than an ac current, both having the same time-averaged (not rms) value.

2.7. Filter Selection

About 10% of the uv light striking the small glass diagonal (R) is reflected downward to the phosphor-coated surface under test. The resulting fluorescent light, along with the portion of the incident light reflected from the vacuum window (S) and from the phosphor surface, then passes upward to a uv-absorbing filter (P) that allows the fluorescent light to pass on to the film (L), or other fluorescence detector, while blocking all other light to which the detector is sensitive. In order to keep the intensity of competing light, in particular the deep-red portion, acceptably low it was necessary to prevent direct reflection

into the camera lens (O) from the main light beam of the uv lamp. These reflections were kept low by proper orientation and shaping of the surfaces in the path of the main beam and by coating them with a flat-black paint.

The effort required to separate the fluorescent light from its competition depended upon the detector employed to view the fluorescence. The simplest situation occurred when the eye was used as the detector, for even with no filter the eye saw only the desired green fluorescence. This was a consequence of the spectral response of the eye and the relative intensities of the competing radiation. In most cases, however, the fluorescence was recorded on film. The film used was sensitive to wavelengths between approximately 360 and 650 nm. Hence the film was blind to the red and infrared light present, but was sensitive to the violet and uv. Many filters are available which absorb violet and uv light. A #2A Wratten gelatin filter, 100 μm thick, was used for the present work. This filter transmits wavelengths longer than about 410 nm [9]. In cases where the uv lamp emits too much blue light, a #8 Wratten filter would be required. This filter transmits wavelengths longer than 470 nm. Because these filters exhibited a weak fluorescence when placed in the direct beam of the uv lamp, they had to be shielded from the strong primary beam of the uv light. One of these filters was also necessary when a photomultiplier tube having an S-11 spectral response was used to measure the phosphor fluorescence. Selenium and silicon photo-voltaic cells were found to be too sensitive to the deep red and infrared transmitted by these filters to be useful.

2.8. Camera Optics

The plain glass diagonal (R) that deflected the uv light onto the TUT was, unavoidably, in the path of the fluorescent light passing from the phosphor coating up to the camera lens. In order to minimize distortion, the diagonal was made as small as permissible, its approximate dimensions being 7.5 mm diameter and 0.1 mm thick. Approximately 1/3 of

the light from the TUT intercepted the diagonal. A totally reflecting
mirror could have been used if more intense uv illumination of the
phosphor were required.

A 50-mm focal length lens, taken from a "35-mm" camera, was used
for the focusing lens (O). A 36-cm long extension tube (N) between the
lens and camera body (M) provided 8X magnification of the TUT. In order
to obtain sufficient working distance between lens and TUT it was
necessary to mount the lens so the end that faces the film when used for
ordinary picture-taking, is facing the TUT instead. The distance
between the TUT and the nearest lens surface was about 50 mm. An un-
desired consequence of using the lens backward is that its speed
becomes approximately f/3.5, although it is rated as f/1.4 when used
normally.

A 35-mm single-lens reflex camera body (M) was used to view the
TUT and to hold the film. In a single-lens reflex camera the same lens
is used to form the image for both the film and the view finder. A
hinged, movable mirror determines in which place the image is formed.
The advantage of this arrangement is that the image seen in the view
finder is always the same as the image recorded by the film.

The viewing screen used in the view finder had a ground glass sur-
face, except for a central circular area that was clear. A fairly
sharp and bright image was visible in the clear region, but accurate
focusing on the TUT was difficult to achieve. The image seen on the
ground glass was of low brightness and never appeared sharply focused,
although focusing accuracy seemed about as good as for the clear region.
As long as the phosphor coating on the TUT fluoresced brightly enough
to produce adequate film exposure with the 35 seconds exposure time used,
it was bright enough to be seen in the clear region of the viewing
screen.

Many viewing screens intended for taking ordinary snapshots are not
satisfactory for photomicroscopy work. In particular, viewing screens
depending on either a split-image rangefinder or a Fresnel viewing
region for focusing are not acceptable. The problem arises because the
light reaching the viewing screen from the TUT has a narrow angular

spread. The small angular spread renders the split-image range finder inoperative. It also accentuates the coarse texture of the Fresnel pattern, and again prevents satisfactory focusing.

2.9. Film and Processing

A fast (ASA speed of 400), panchromatic black-and-white film[6,7] was employed. An exposure time of 35 seconds was used in photographing the phosphor fluorescence. For this exposure time a light intensity of approximately 0.0001 meter-candles at the film is required to produce the minimum usable film exposure [10]. This minimum usable exposure limited the highest temperature measurable on the TUT to approximately 210°C for the combination of uv intensity, film, camera optics, and exposure time selected. The resolution of the film, for a high contrast subject, was estimated to be 30 line-pairs per millimeter.

2.10. Microdensitometer

The microdensitometer employed automatically made a straight-line scan across the film, producing an ink-on-paper recording of film density versus position. For the purpose at hand the microdensitometer was set up to produce recordings having a calibration factor of 0.15 density units per centimeter in the vertical direction, and a 10-mm displacement in the horizontal direction for a 1-mm displacement at the film.

Photographic density is defined as the logarithm (to the base ten) of the ratio of incident light flux to the light flux transmitted by the film. Thus if the film transmits 50% of the incident light, its

---

[6]Kodak Tri-X Pan Film, TX 135-20.

[7]Film was developed in full-strength Kodak D-76 developer at 24°C. Development time was 10 min, with agitation for about 4 seconds at half-minute intervals.

density is 0.30 du (du = density unit). After making a number of density measurements on the film negatives, it was noticed that the graph of density versus exposure had about twice the slope that was shown by the published film data [10]. The discrepancy was probably due to the fact that the measured value of density is dependent upon the details of the optical system used to make the measurement. It turned out that it is standard film-industry practice to specify the diffuse density of films. The term diffuse density means that when measuring the transmitted light flux, all transmitted light is included. However, the instrument used by the author did not measure the total transmitted flux, but only that portion which passed straight through the film and could thus be collected by the microscope objective of the microdensitometer; light scattered by the film was not detected. The diffuse density of any scattering medium is always less than the density indicated by the author's instrument. When quantitative values of film density are given in this report, the values are the net density above the fog and base density of the film, as measured with the microdensitometer used by the author.

A square scanning aperture, either 200 or 400 μm on an edge with respect to the film, was used when making the microdensitometer recording. Since the film image was an 8X enlargement, the scanning aperture with respect to the TUT was either 25 or 50 μm on an edge.

2.11. Film Image Evaluation

The raw data produced by each experiment was a filmstrip of negative transparencies of the fluorescent surface of the TUT. From these negatives the temperature profile of the transistor could be obtained. The method used to obtain temperature data from the negatives is described in this section.

It is convenient to divide the negatives into two categories; calibration negatives and operating negatives. A calibration negative is simply a picture of the phosphor surface taken when no power was

applied to the transistor, so that the entire surface was at the temperature of the heat sink. (The resistance heaters mounted in the heat sink brought it to the desired test temperature.) Therefore the negative is a record of the radiance of the phosphor fluorescence for this temperature. A set of calibration negatives is shown in figure 6a. Note that although all parts of the transistor were at the same temperature, the density of each negative varies from point to point. For this reason intercomparison of negatives had to be made on a point-by-point basis when temperature data was sought.

An operating negative is a picture taken when the TUT was dissipating electric power. Figure 6b shows a typical operating negative. Although the location and approximate temperature of the hot spot can be seen at a glance, quantitative temperature measurements can be obtained only by correlating an operating negative with the calibration negatives. This correlation was accomplished by using a microdensitometer to generate a family of density (temperature)-_versus_-position traces from the calibration negatives, upon which a corresponding trace from an operating negative was then superimposed (fig. 6c). Each trace covered exactly the same path across the transistor surface, so a vertical line drawn on this graph corresponds to a particular point along the path. Wherever the trace of the operating negative intersects a calibration trace, its temperature is known. Hence these intersections establish the temperature profile along the line scanned.

The temperature profile of the entire surface of the TUT can be built up from the temperature profiles of individual lines, but this is a very slow process unless the procedure is automated. Most of the negatives evaluated in this project were scanned along only one path, chosen to include the hot spot of the TUT. Blanks [1] used two projectors, a single reference negative, and a differential light meter to measure film density, a procedure that is faster but less accurate than that used here.

Since all negatives had to be scanned along the same path on the transistor image, reference markers were placed on two corners of the transistor chip before photographs were taken. This was done by removing
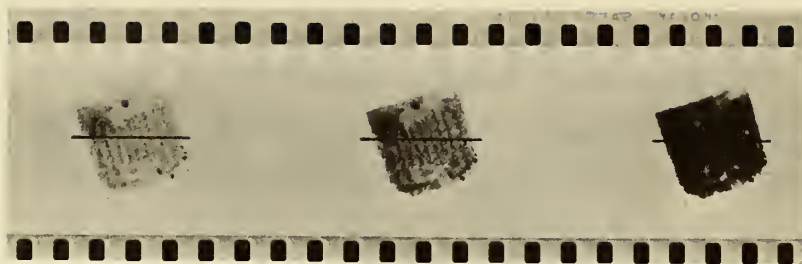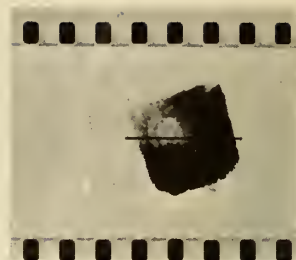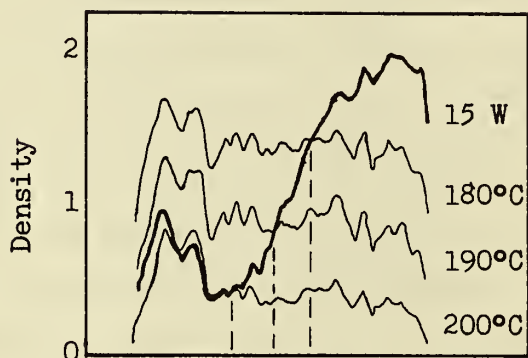
(a) Calibration negatives.

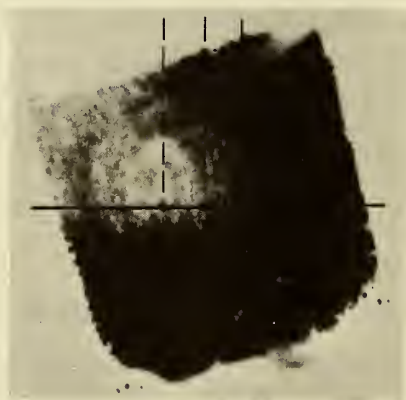200°C   190°C   180°C

(b) Operating negative.

15 watts

(c) Microdensitometer traces of negatives along indicated path.

(d) Temperatures plotted on an enlargement of the operating negative.

Figure 6.   ANALYSIS OF FILM NEGATIVES. The negatives in (a) and (b) are about the size of those examined by the microdensitometer. The emitter lead is at the bottom of the chip, the base lead at the top. Contrary to the case shown here, all other transistors tested developed their hot spot near the emitter lead.

the phosphor from the corners and placing a few grains of another phosphor on the cleared area. One grain at each corner was arbitrarily chosen for use as the position reference. The marker phosphor maintained a reasonably strong fluorescence throughout the temperature range used for the calibration negatives. Grains of marker phosphor are seen in the lower two corners of the chip in figure 6d. The dark spots in figure 6a were caused by misplaced marker phosphor.

3. ANALYSIS AND EVALUATION

3.1. Purpose and Conventions

Many of the characteristics and limitations of temperature-sensitive phosphors were revealed by correlating microdensitometer recordings of the film negatives with the test conditions under which the exposures were made. The purpose of this section is to present the relevant experimental data and from this establish the characteristics of the phosphor. In order to simplify the presentation it is desirable to adopt the convention that length dimensions on the film will be referenced to the transistor surface. Or if the film image is not that of a transistor, then film dimensions will be referenced back to an imaginary transistor. If, for example, the microdensitometer aperture views a 400 x 400 μm area of the film, the text will state that the aperture is 50 x 50 μm, it being understood that the dimensions at the film have been divided by 8 in order to reference the measurement to the transistor.

3.2. Stability of Transistor Parameters

The transistors were subjected to some vigorous treatment while they were test objects. Each transistor had its protective cap removed, and the transistor chip was likely to be subjected to various organic solvents, water, detergent, mechanical rubbing, weeks of exposure to phosphor and air, and high-temperature operation in vacuum. Surprisingly, the effect of these operations upon electrical parameters of the transistors appeared to be negligible.

The common-emitter current gain (β) and the collector-to-base leakage current (I_{CBO}) of two or three samples of each of the three transistor types investigated were measured <u>before</u> their cases were opened. The β tests were made with the transistors dissipating 2 W and at medium to high collector currents. The I_{CBO} measurements were made at several voltages ranging from about 20% to nearly the maximum of the

published collector junction breakdown voltage. Measurements of both β and I_{CBO} were first made with the heat sink at 25°C, then repeated at 125°C, and finally rerun at 25°C. Changes in β of ±2% between the two 25°C tests were common, but never exceeded ±4%. A similar comparison for I_{CBO} produced changes as large as -65% and +100%. Large changes in I_{CBO} were common, although one of the transistors changed only about 12%. These parameters were also measured on three of the transistors at the end of their use as temperature measurement subjects. For all three the changes that occurred before their cases were opened were larger than those occurring afterward.

The above measurements of β and I_{CBO} were made with the exposed silicon chip in darkness to avoid a photo-current of approximately 100 μA that would be produced by irradiation from the uv lamp. The good stability of the electrical parameters of the exposed chips may have been due to the vacuum environment that was provided when the chips were operated at high temperature.

3.3. Phosphor Characteristics

The dependence of the phosphor's fluorescent radiance upon temperature and uv irradiation was measured and is shown in figure 7. The fluorescence was measured by replacing the camera and lens assembly with a photomultiplier tube having an S-11 spectral response. Important characteristics of the phosphor that were revealed are:

1) For a given intensity of uv irradiation there is a span of approximately 50°C over which the temperature coefficient of fluorescent brightness is essentially constant and near its maximum value of 6.1%/°C.

2) Increasing the intensity of the uv irradiation by a factor of three causes the entire temperature span of maximum sensitivity to shift approximately 20°C upward.
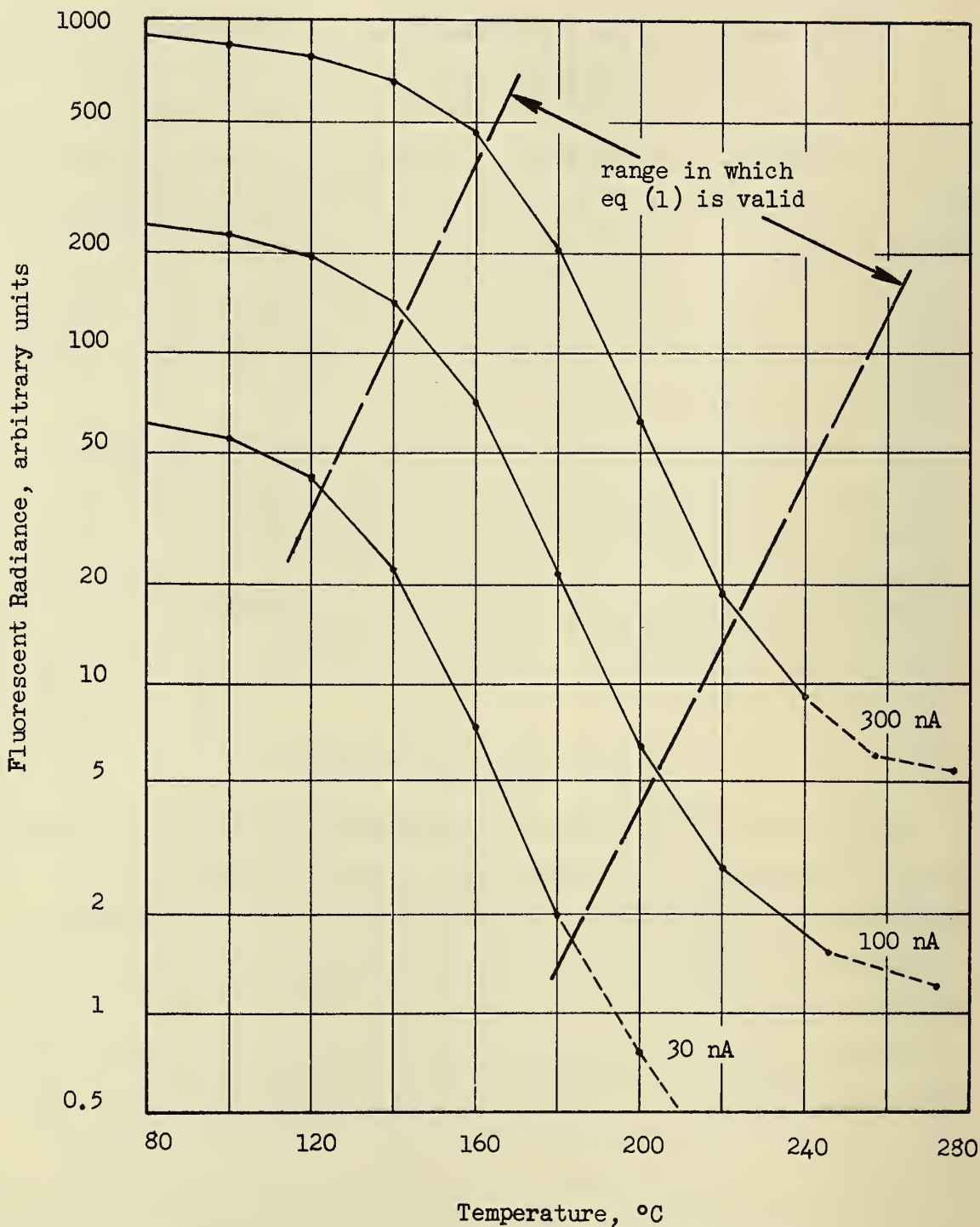
Figure 7. FLUORESCENT RADIANCE OF #2090 PHOSPHOR AS A FUNCTION OF TEMPERATURE AND UV EXCITATION. The phosphor is a thin, somewhat open coating on an aluminum plate. The uv excitation for each curve is identified by, and is approximately proportional to, the cathode current developed by the uv monitoring vacuum photodiode. Dashed lines show experimental data whose accuracy is not assured.

30

3) If the phosphor is held at some fixed temperature with-
   in the span of high sensitivity, then the fluorescent
   radiance is proportional to the 1.9 power of the uv in-
   tensity. In other words a 10% change in uv irradiation
   causes 19% change in the radiance of the fluorescence.
   This large sensitivity of radiance to the uv intensity
   is a consequence of the fact that the temperature at
   which the brightness begins to drop sharply, changes
   with the uv irradiation.

The following empirical equation is useful for interpolating the
data given in figure 7:

$$R_2 = (I_2/I_1)^{1.9} R_1 (1.061)^{(T_1 - T_2)} \qquad \text{when} \qquad (1)$$

R = radiance of fluorescence in arbitrary units,
I = uv irradiation incident on the phosphor in arbitrary units,
T = temperature of phosphor in degrees Celsius.

Subscripts 1 & 2 identify initial and final states, respectively. This
equation is valid only if the temperature coefficient of brightness is
near its maximum value of 6.1%/°C at both points. Figure 7 can be used
to determine whether this requirement is satisfied.

3.4. Heat Transfer

For the calibration negatives the temperature of the surface of
the transistor chip was very close to the temperature of the heat sink.
To demonstrate that this was the case, the maximum possible temperature
difference was calculated as follows: The total radiated power from a
1.5 x 1.5 mm black-body surface at 200°C, calculated from the Stefan-
Boltzmann 4th-power radiation law, is less than 30 mW. And based on
the heater power required to maintain the heat sink at 200°C, heat loss
from the heat sink surface to the residual air around it was less than
5 mW/mm^2, making the conductive heat loss from the surface of the sili-
con chip less than 10 mW. The thermal resistance from collector

31

junction to heat sink was less than 10°C/W, so the temperature differ-
ence between collector junction and heat sink was less than 0.4°C even
when the most pessimistic assumptions were made.

No independent measurement of transistor surface temperature was
made while transistors were dissipating electric power. Independent
measurement would have required the use of an infrared microradiometer
and was beyond the scope of this project.

The mechanism of heat transfer from the transistor surface to the
phosphor was the same for both the calibration and the operating
negatives. In both cases heat was conducted from the transistor sur-
face into the phosphor layer. Temperature differences between tran-
sistor and phosphor, if any, were probably the same for both the cali-
bration and the operating negatives, and were therefore accounted for
by the calibration negatives.

3.5. Temperature Range

The temperature range over which useful measurements could be made
was influenced by many parameters, some of which could be selected to
suit the requirements of the user. For any set of parameters chosen,
the useful temperature range was easily found by examining the film-
density versus phosphor-temperature characteristic obtained. Figure 8
shows this characteristic for the parameters used in the present in-
vestigation. At temperatures between 180 and 200°C the relation of
film density to phosphor temperature remained fairly constant at approx-
imately 0.05 density units (du) per Celsius degree. At temperatures
below 180°C the sensitivity fell off because the phosphor fluorescence
became less temperature dependent. Above 200°C the sensitivity dropped
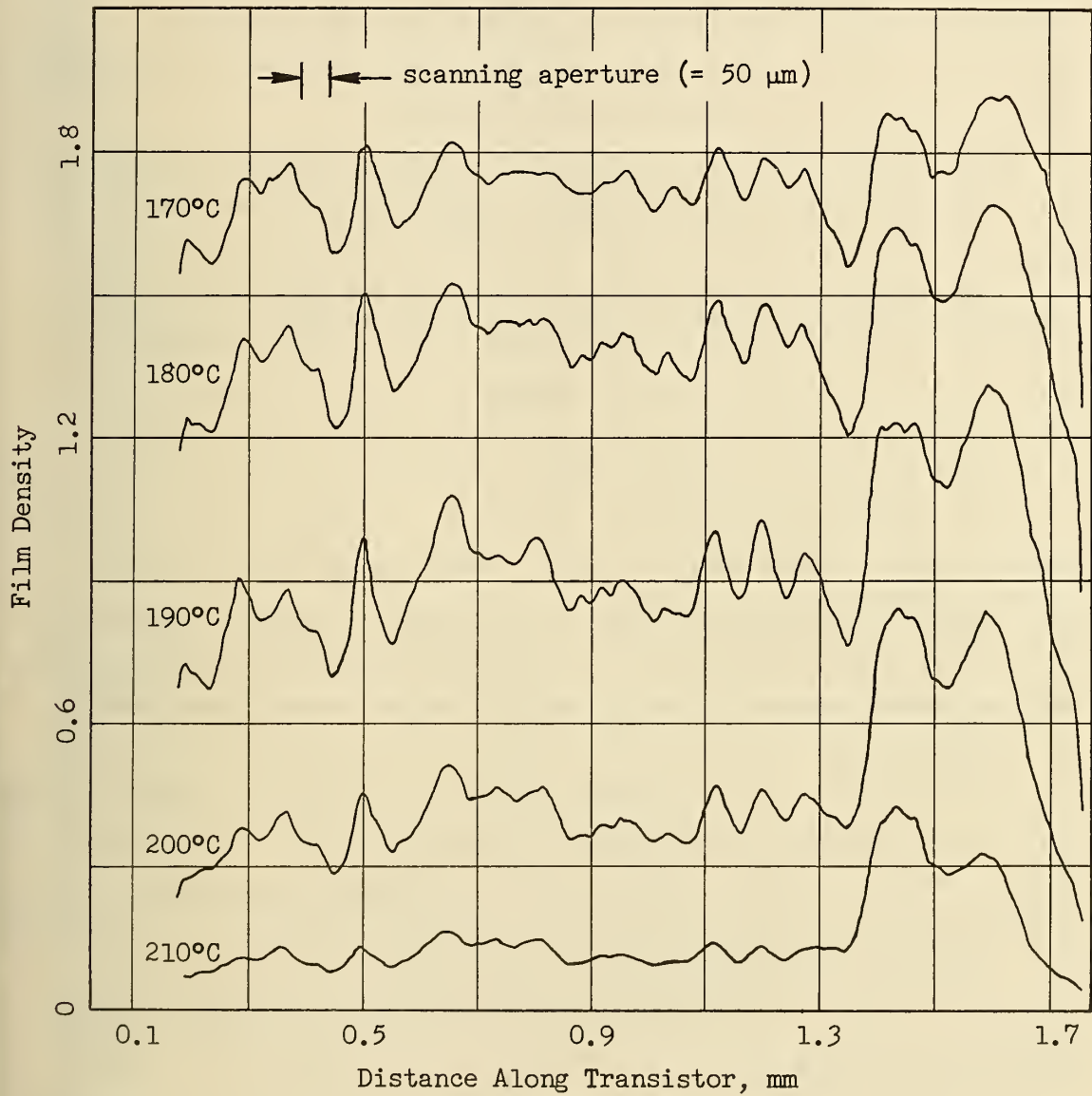sharply because the fluorescence became too weak to produce an image on
the film.

Figure 8.   FAMILY OF CALIBRATION NEGATIVE TRACES.

3.6. Limitations of the Film

Ideally, the photographic density of the film should have been determined only by the brightness pattern of the phosphor fluorescence. In fact, the film itself had small inherent density variations. Although these variations warranted consideration, they were not a major source of error in the temperature measurements.

The microdensitometer recordings in figure 9 display the density variations inherent in the film itself. Each exposure was made by removing the camera lens and uniformly illuminating the film, so local variations of the film density could not be attributed to exposure variations. Since temperature measurements were made by matching the densities of two negatives at the same point along a scanning path, only frame-to-frame variations at a particular point are significant. The largest variations observed were 0.05 and 0.03 du for 25 x 25 μm and 50 x 50 μm scanning apertures, respectively. In other words, the variations caused no more than 1°C error. These values applied for any pair of negatives on the same roll of film when the density was about 1.0 du. The density variations of unexposed frames were always smaller than for frames exposed to light, so dust or dirt on the negatives was not a factor here.

The boundaries around highly localized hot spots were regions across which the radiance of the phosphor fluorescence usually changed very rapidly. This resulted in steep exposure gradients on the camera film, a condition that could conceivably have modified the expected film density. Although these exposure gradients probably did not introduce significant errors, as a precautionary measure the phenomenon will be explained more fully.

The nature of the effect can be demonstrated by making a microdensitometer trace across the boundary between two regions that have received different exposures. Ideally, the recording should show a simple step change in the film density. But in practice a slight overshoot usually occurs on both sides of the transition [11], as seen at the left-hand side of the traces in figure 9. This is caused by the action of
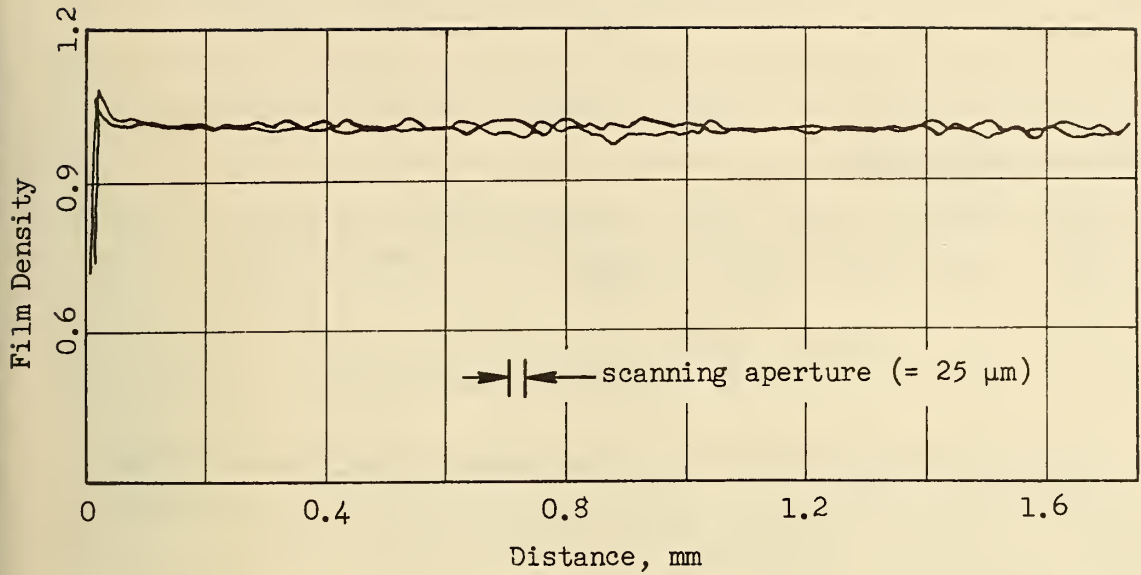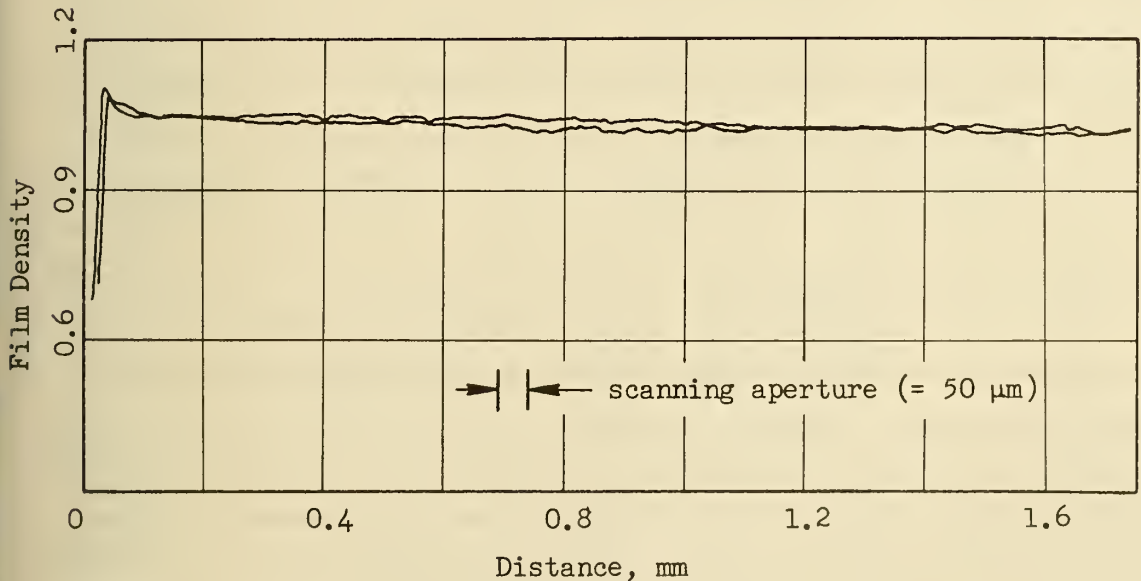
Figure 9. DENSITY VARIATION INHERENT IN THE FILM. The density struc-
ture of negatives that were exposed by a uniform blanket of
light is shown. Each graph shows the results for two frames
on the same filmstrip. The same negatives and scanning path
were used for both (a) and (b).

the film developer. The developing solution becomes somewhat depleted in the area that received the greater exposure. Some of this depleted developer diffuses into the area of lesser exposure, depressing the amount of development in that region. At the same time, strong developer from the area of lesser exposure also diffuses across the boundary, causing increased development of the heavily exposed image.

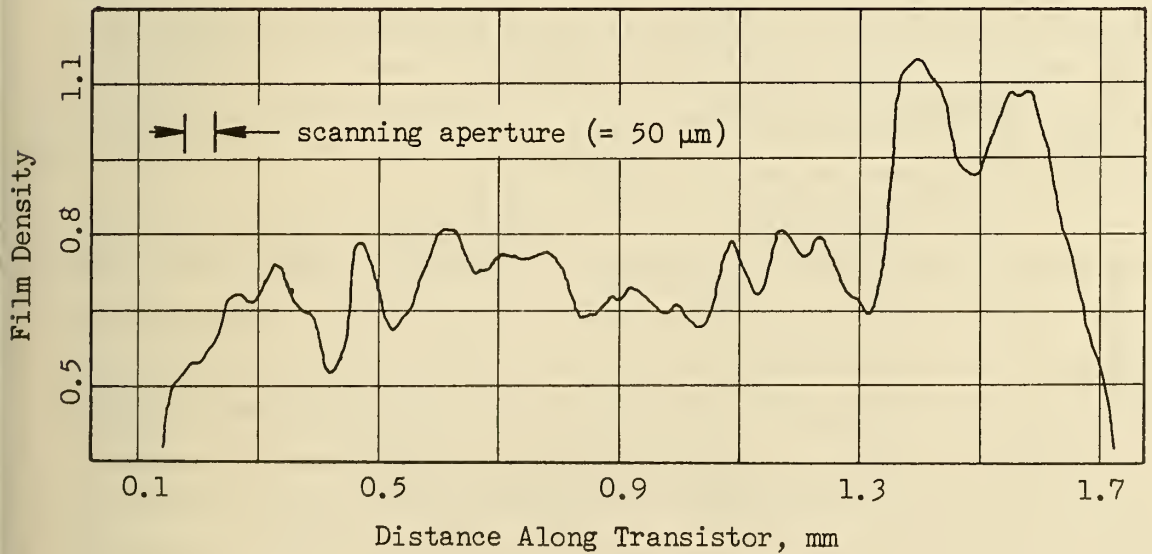## 3.7. Calibration Negatives

Examining a single calibration photograph reveals several important characteristics of the TSP. Microdensitometer scans across a typical calibration negative are shown in figure 10. The negative is a photograph of the fluorescence of a phosphor-coated transistor at 190°C. Keeping in mind that the entire phosphor-coated surface was at the same, uniform temperature, the most striking feature of the recording is its jagged structure. Ideally, the radiance of the phosphor fluorescence would have been the same everywhere. The density variations seen in this recording were caused primarily by unevenness of the phosphor coating. Clumps of phosphor grains, which fluoresced brightly, produced the density peaks, while the valleys usually correspond to thinner and more uniform regions of the coating. The deep valley about 0.4 mm along the scanning path, however, was caused by a void in the phosphor layer.

One of the limitations of the TSP was caused by these variations in the phosphor coating. Notice that they produced density gradients that are typically 7 du/mm. The film could be positioned in the micro-densitometer within an overall error span of 15 μm, with respect to the surface of the actual transistor. It was unusual, however, for this span to exceed 7 μm. This means that when the calibration negative was temporarily removed, and then returned again to the microdensitometer, its new position usually differed from the original position by less than 7 μm. If a positioning error of 7 μm did occur, then density readings on the new scan might change (0.007 mm) x (7 du/mm), or 0.05 du. In practice, discrepancies were usually somewhat less than this, even
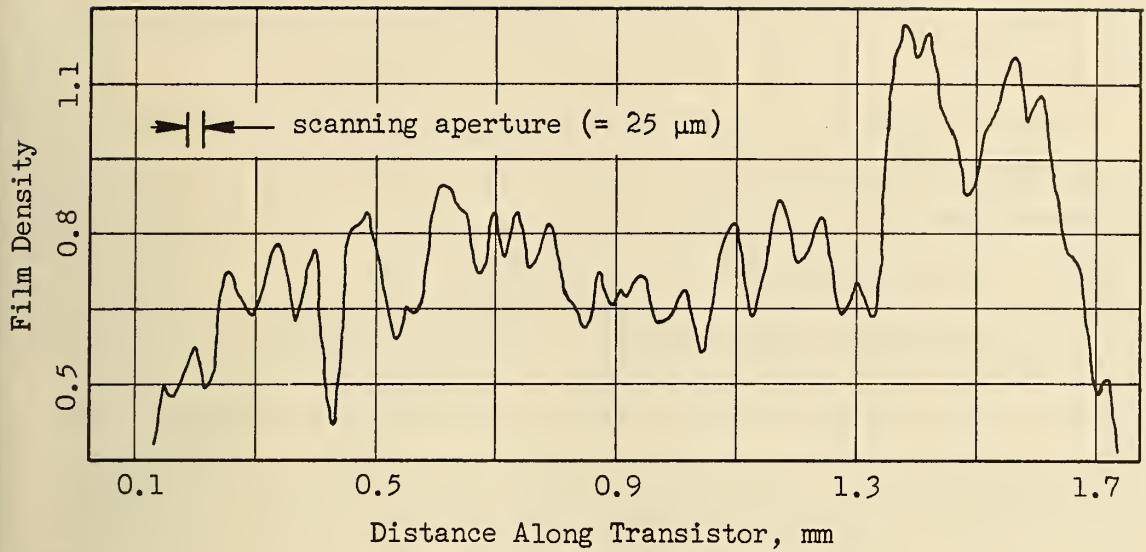
Figure 10. DENSITY STRUCTURE OF A CALIBRATION NEGATIVE. The two curves show the smoothing that occurs when a larger scanning aperture is used. Both scans were made along the same path on the same 190°C calibration negative.

when several months elapsed between examinations and the negative received moderate handling.

Figure 10b shows the recording obtained when the scanning path of figure 10a was retraced, but with a 50 x 50 μm aperture. The larger aperture is seen to substantially reduce the slope of the curve over most of the recording. Density peaks that appear in this recording were caused primarily by the thicker phosphor coating that deposited on the transistor metallization. A minor benefit of the larger aperture was that the peaks and valleys that appeared in the microdensitometer recording corresponded to the brightness variations seen by direct visual observation of the phosphor. When the small aperture was used, the local detail that was obtained tended to obscure the nature of the overall picture.
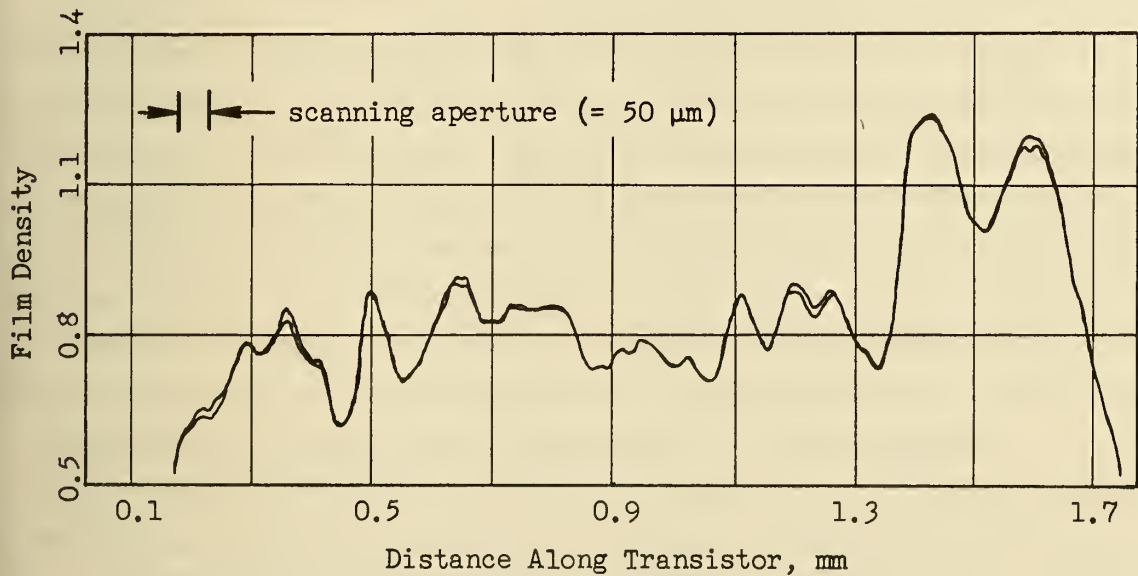
3.8. "Identical" Negatives

The preceding section discussed the reproducibility that was obtained when duplicate microdensitometer recordings were made of the same negative. The present section will discuss the reproducibility obtained by "identical" negative pairs. Or in other words, did identical exposures produce identical negatives?

Calibration negatives, all of the same transistor held at the same temperature, were used to evaluate photographic reproducibility. The test conditions for each exposure were as identical as the experimental equipment could make them. To this end, only negatives from the same filmstrip were compared, and all exposures were made during the same run in order to minimize possible shifting of the phosphor. It was found to be immaterial whether the exposures were adjacent frames or were at opposite ends of the filmstrip. Applying power to the transistor between calibration exposures also had no effect on the results.

The microdensitometer recordings in figure 11 show the reproducibility that was typically achieved between two "identical" negatives. The largest discrepancy observed between such negative pairs at any one point was 0.1 du for the 25 x 25 μm aperture, and 0.05 du for the
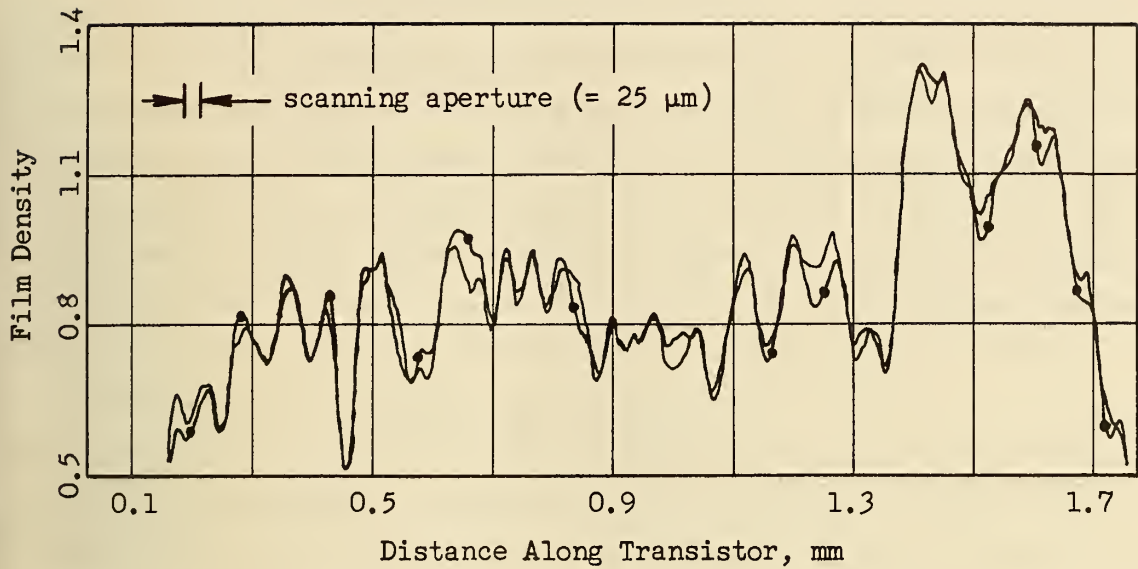
(a)

(b)

Figure 11. DENSITY VARIATION BETWEEN "IDENTICAL" CALIBRATION NEGATIVES.
Figure _a_ shows microdensitometer traces for two "identical"
190°C calibration negatives, each scanned along the same
path. Dots are used to distinguish between the two nega-
tives. Figure _b_ repeats the traces using a larger aperture.

50 x 50 μm aperture. Such frame-to-frame differences were the predominant source of error in the temperature measurements and seemed to be caused by spontaneous changes in the position of individual phosphor particles. These density variations were around three times larger than the inherent variation in the film itself, and about twice as great as the density discrepancies observed between repeated scans of the same negative.

3.9. Spacial Resolution

As used in this section, spacial resolution refers to the ability of a phosphor coating to resolve fine patterns of surface temperature. Because it is difficult to produce temperature variations having high spacial frequency and at the same time accurately known temperatures within the temperature pattern, only qualitative measurements of spacial resolution were obtained.

Visualize a surface divided into two isothermal regions with an infinitely sharp gradient at their common boundary. The spacial resolution of a temperature-measuring system can be evaluated by noting the distance required for its temperature reading to go from one temperature to the other as the boundary is traversed. The transition distance cannot be smaller than the scanning aperture used. In addition to aperture several other factors can also limit resolution. Among these are the diffusion of heat once it passes into the phosphor coating, and the possibility that the photographic optics may not form a sharp image on the film. Or, fluorescent light from the cool (brighter) side of the transition might illuminate the phosphor on the hot side of the boundary. The steepest gradient actually found was a temperature change of 40°C that occurred over a distance of 0.09 mm, or 450°C/mm. It is not known whether this was the gradient actually existing on the transistor, or if the observed gradient represented a limitation of the TSP technique.

Since the use of the larger, 50 x 50 μm scanning aperture improved

the repeatability of the temperature measurement, it became desirable to know whether or not spacial detail of the temperature profile was sacrificed for this benefit. A test for this was made by scanning a negative first with the 25 x 25 μm aperture and then with the 50 x 50 μm aperture. The operating negative that showed the narrowest hot spot was selected for this test. The small aperture characterized the hot spot as having a peak temperature of 197°C, and a width of 140 μm between the points that were at 190°C. The large aperture characterized the hot spot as having essentially the same peak temperature, and a width of 160 μm between the 190°C points. Thus for all temperature profiles encountered, the larger scanning aperture appeared to provide adequate spacial resolution.

3.10. Stray Light

Since temperatures could vary widely on the surface of an operating transistor, brightness of the phosphor fluorescence could also vary greatly from point to point. When a wide brightness range existed, there was the possibility that light from bright areas would illuminate the darker areas. Such illumination would degrade measurements in the darker (hotter) areas because the spurious light was not present when the high-temperature calibration photographs were taken. This characteristic is an inherent weakness of the TSP technique. Means by which spurious illumination was kept to a minimum were:

1) Limiting the phosphor-coated area to only the regions whose temperature was to be determined.

2) Designing the test chamber to prevent reflection of fluorescent light back to the phosphor coating.

3) Selecting the uv intensity so as to limit the brightness ratio over the phosphor surface. This requirement was met by using the lowest uv intensity that allowed measurements to be made over the temperature range required.

A certain amount of the light passing from the phosphor surface to the film was probably scattered by items in its path. The scattering mechanisms would include dust particles and multiple reflections from the surfaces of optical components. The overall effect of such scattered light would be to cause a slight, uniform exposure over the entire film, thus tending to fill in the areas of minimum exposure. For the equipment used, stray light was believed to be only a minor problem, because when sufficiently high hot-spot temperatures were produced, there was no measurable film exposure in the hot spot region, even though the rest of the phosphor fluoresced brightly.

3.11. Vacuum and Air Environments

Comparison tests were made to determine if a temperature change resulted when the transistor environment was changed from a pressure of about 10^{-4} atmosphere to almost full atmospheric pressure, all other parameters, including heat sink temperature, remaining constant. The hot-spot temperature was about 200°C during these tests. Nearly identical operating negatives resulted, well within the normal frame-to-frame variation discussed in 3.8. This test was not done for calibration negatives because the copper heat sink would have been subject to excessive oxidation if exposed to air at elevated temperatures.

3.12. Irreversible Effects

An irreversible change in the phosphor fluorescence was observed with two transistors. In both cases the transistors had been operated under conditions that caused the hot-spot temperature to become unusually high. This caused a portion of the phosphor to develop a permanent increase in the brightness of its fluorescence for all temperatures. The temperature required to produce the irreversible effect was estimated to be in the vicinity of 270°C. The transistor used as the subject for the microdensitometer recordings shown in this chapter had

such a temperature-modified region of phosphor. This region is identi-
fied by its abnormally high photographic density. Note, for example,
the portions of the recordings in figure 8 that fall between 1.3 and
1.7 mm along the scanning path.

Temperatures that caused the irreversible change in fluorescence
also caused some of the phosphor to permanently bond to the aluminum
metallization on the transistor chip. The lowest temperature required
to produce bonding was not determined.

3.13. Practical Results

Figure 12 shows the kind of single-path temperature profile that
was obtained from the filmstrips when evaluated as described in Section
2.11. The profile path was usually chosen to pass through the point of
highest temperature. Such a path was easily found because the location
of the highest hot-spot temperature could be readily identified by
direct visual examination of the operating negatives.

In principal the temperature profile of a complete surface could
have been built up from a large number of single-line profiles. But as
a practical matter, production of a complete profile was found to be
too time consuming and was not attempted. It was estimated that approx-
imately five hours would have been required to produce a single, rather
coarse, overall temperature profile composed of six lines having five
temperature calibration points each. However, the time would probably
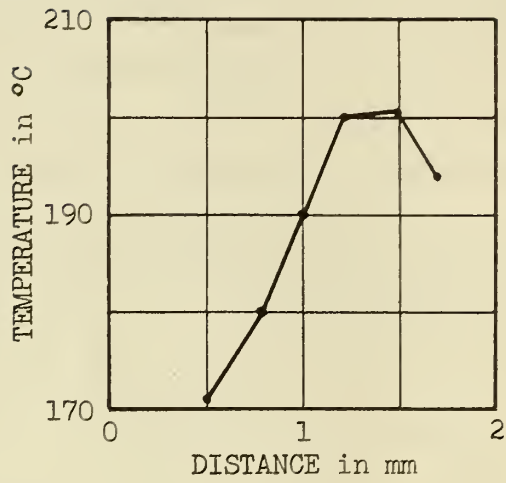be reduced by half if somewhat reduced accuracy were acceptable.

Figure 12. TEMPERATURE PROFILE ALONG PATH THROUGH A HOT SPOT.
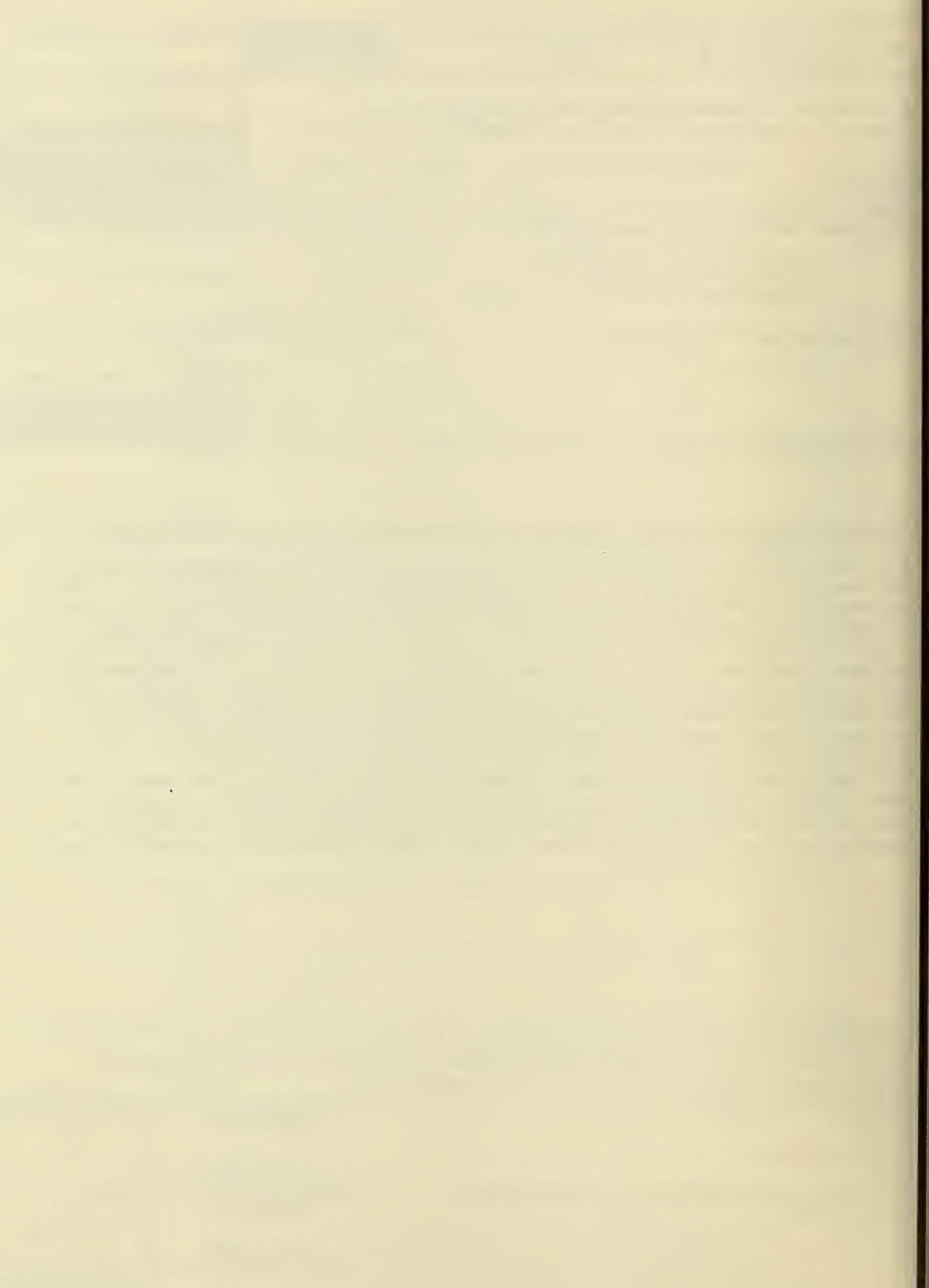The profile is based on figures 6c and 6d.

4. SUMMARY

Temperature-sensitive phosphor (TSP) provides a very easy means for obtaining a visual, <u>qualitative</u> indication of surface temperature. This report has shown that TSP can also provide <u>quantitative</u> temperature measurements. With the apparatus used, and over the range of 170-210°C, measurements were always reproducible to within an overall range of 4°C when the phosphor surface was scanned with a 25 x 25 μm aperture, and to within 2°C when scanned with a 50 x 50 μm aperture. The predominant cause of measurement error seemed to be spontaneous changes in the position of individual phosphor particles. Unevenness of the phosphor coating limited the smallest useful scanning aperture to about 20 x 20 μm. Surfaces having only moderate temperature variations could be easily calibrated to make the measurement accuracy about the same as its reproducibility. The accuracy obtained for surfaces having wide temperature variations appeared to be almost as good, but a thorough investigation of this case was not made.

The handling and processing received by the transistor chips did not significantly affect their electrical parameters. The phosphor coatings were deposited without using a binder and were easily removed from the chips at the end of the tests, providing that temperatures had not greatly exceeded 210°C. At higher temperatures some of the phosphor permanently bonded to the bare aluminum metallization.

5. REFERENCES

[1] Blanks, H. S., Thermographic analysis of electronic components
     (Proc. of the Inst. of Radio and Electronics Engineers
     Australia) 29, 337-342 (Oct. 1968).

[2] Goryunov, N. N., Ovechkin, Yu. A., Tolkacheva, Ya. A., and
     Feoktistov, Yu. F., Observation of thermal fields in semiconduc-
     tor devices, Instruments and Experimental Techniques (USSR),
     439-443 (Mar.- Apr. 1966).

[3] Young, M. R. P., and Peterman, D. A., Reliability Engineering,
     Microelectronics and Reliability, 7, 91-103 (1968).

[4] Peterman, David, and Workman, Wilton, Infra-Red radiometry of semi-
     conductor devices, Microelectronics and Reliability, 6, 307-315
     (1967).

[5] Reich, Bernard, and Hakin, Edward B., An appraisal of transistor
     thermal resistance measurement techniques, SCP and Solid State
     Technology, 8, 21-29 (Apr. 1965).

[6] Fergason, J. L., Liquid crystals, Scientific American, 211, 76-85,
     (Aug. 1964).

[7] Urbach, F ., Nail, N. R., and Pearlman, D., The observation of tem-
     perature distributions and of thermal radiation by means of non-
     linear phosphors, J. Opt. Soc. Am., 39, 1011-1019 (Dec. 1949).

[8] Byler, W. H., and Hays, F. R., Fluorescence thermography, Nonde-
     structive Testing, 19, 177-181 (May-June 1961).

[9] Kodak Publication No. B-3, Kodak Wratten Filters, 20th Edition
     (1960).

[10] Kodak Photo Information Book AF-13, Kodak Black-and-White Films in
     Rolls, 3rd Edition (1967).

[11] Kodak Scientific and Technical Data Book P-9, Kodak Photographic
     Films and Plates for Scientific and Technical Use, 8th Edition
     (1960).

16. ABSTRACT (A 200-word or less factual summary of most significant information. If document includes a significant bibliography or literature survey, mention it here.)

A technique that uses temperature-sensitive phosphor (TSP) to make quantitative measurements of transistor-chip surface temperatures over the range of 170 - 210°C is described. The experimental procedure consisted of depositing a thin coating of phosphor on uncapped power transistors, and then photographing the visible fluorescence generated under near-ultraviolet (uv) excitation. The cooler regions produced a brighter fluorescence than the hotter areas. The surface temperatures of operating transistors were determined by comparing, on a point-by-point basis, the photographic density of operating photographs to the density of a family of calibration photographs. Repeated temperature measurements always fell within a 4°C overall error range when the phosphor surface was scanned with a 25 x 25 μm aperture. The error band dropped to less than 2°C when a 50 x 50 μm aperture was used. Coarseness of the phosphor coating seemed to limit spacial resolution to about 20 μm. Any narrow temperature range between 20 and 400°C can probably be measured by selecting a suitable level of uv irradiation and/or a suitable phosphor.

NBS TECHNICAL PUBLICATIONS

PERIODICALS

JOURNAL OF RESEARCH reports National Bureau of Standards research and development in physics, mathematics, chemistry, and engineering. Comprehensive scientific papers give complete details of the work, including laboratory data, experimental procedures, and theoretical and mathematical analyses. Illustrated with photographs, drawings, and charts.

Published in three sections, available separately:

● Physics and Chemistry

Papers of interest primarily to scientists working in these fields. This section covers a broad range of physical and chemical research, with major emphasis on standards of physical measurement, fundamental constants, and properties of matter. Issued six times a year. Annual subscription: Domestic, $9.50; foreign, $11.75*.

● Mathematical Sciences

Studies and compilations designed mainly for the mathematician and theoretical physicist. Topics in mathematical statistics, theory of experiment design, numerical analysis, theoretical physics and chemistry, logical design and programming of computers and computer systems. Short numerical tables. Issued quarterly. Annual subscription: Domestic, $5.00; foreign, $6.25*.

● Engineering and Instrumentation

Reporting results of interest chiefly to the engineer and the applied scientist. This section includes many of the new developments in instrumentation resulting from the Bureau's work in physical measurement, data processing, and development of test methods. It will also cover some of the work in acoustics, applied mechanics, building research, and cryogenic engineering. Issued quarterly. Annual subscription: Domestic, $5.00; foreign, $6.25*.

TECHNICAL NEWS BULLETIN

The best single source of information concerning the Bureau's research, developmental, cooperative and publication activities, this monthly publication is designed for the industry-oriented individual whose daily work involves intimate contact with science and technology—*for engineers, chemists, physicists, research managers, product-development managers, and company executives.* Annual subscription: Domestic, $3.00; foreign, $4.00*.

* Difference in price is due to extra cost of foreign mailing.

NONPERIODICALS

Applied Mathematics Series. Mathematical tables, manuals, and studies.

Building Science Series. Research results, test methods, and performance criteria of building materials, components, systems, and structures.

Handbooks. Recommended codes of engineering and industrial practice (including safety codes) developed in cooperation with interested industries, professional organizations, and regulatory bodies.

Special Publications. Proceedings of NBS conferences, bibliographies, annual reports, wall charts, pamphlets, etc.

Monographs. Major contributions to the technical literature on various subjects related to the Bureau's scientific and technical activities.

National Standard Reference Data Series. NSRDS provides quantitative data on the physical and chemical properties of materials, compiled from the world's literature and critically evaluated.

Product Standards. Provide requirements for sizes, types, quality and methods for testing various industrial products. These standards are developed cooperatively with interested Government and industry groups and provide the basis for common understanding of product characteristics for both buyers and sellers. Their use is voluntary.

Technical Notes. This series consists of communications and reports (covering both other agency and NBS-sponsored work) of limited or transitory interest.

Federal Information Processing Standards Publications. This series is the official publication within the Federal Government for information on standards adopted and promulgated under the Public Law 89–306, and Bureau of the Budget Circular A–86 entitled, Standardization of Data Elements and Codes in Data Systems.

Consumer Information Series. Practical information, based on NBS research and experience, covering areas of interest to the consumer. Easily understandable language and illustrations provide useful background knowledge for shopping in today's technological marketplace.

NBS Special Publication 305, Supplement 1, Publications of the NBS, 1968-1969. When ordering, include Catalog No. C13.10:305. Price $4.50; foreign, $5.75.

Order NBS publications from: Superintendent of Documents
Government Printing Office
Washington, D.C. 20402