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Semiconductor Measurement Technology:

A Production-Compatible Microelectronic Test Pattern for Evaluating Photomask Misalignment

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Semiconductor Measurement Technology:
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by

T. J. Russell and D. A. Maxwell

Abstract: Microelectronic test pattern NBS-15 is composed of several potentiometric, production-compatible electrical alignment resistor test structures, visual alignment indicator test structures, cross bridge sheet resistors, and contact resistor test structures. The pattern was originally designed as a study vehicle for the electrical alignment resistor, but it was also demonstrated that, when stepped over an entire wafer, the pattern is suitable for use in evaluating misalignment which may result from photomask generation, photomask exposure, or other fabrication processes. This report summarizes the test structures that are included in the pattern and contains explanation of how each of the structures is measured.

Key Words: Contact resistor, cross bridge sheet resistor; electrical alignment resistor; semiconductor; silicon; test pattern; test structures; visual alignment.

1. INTRODUCTION

Microelectronic test pattern NBS-15 was designed to study several designs of a potentiometric, production-compatible electrical alignment resistor test structure and to compare these to a sensitive visual alignment indicator test structure. Results of our studies show that any of the electrical alignment resistors can be used to quantitively measure the misalignment between two photomask levels with a resolution of about 0.1 μm [1]. The purpose of this report is to describe the test structures included in the NBS-15 test pattern and to indicate how they and the test pattern can be used.

The electrical alignment resistor is measured using dc techniques. Since it can be tested on an automated integrated circuit wafer prober, data can be collected much more quickly using the electrical alignment test structure than they can be using visual alignment test structures. Because of the additional potential for computer-controlled measurement,

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data can be rapidly obtained and analyzed for assessing photomask alignment and determining causes for misalignment when the structure is stepped across an entire wafer.

Test pattern NBS-15 was designed for a three-photomask-level process to produce doped regions, contact windows, and metal probe pads and interconnects. The doping can be done either by diffusion or by ion implantation.

2. DESCRIPTION OF THE TEST STRUCTURES

For the three-level process used here, two types of potentiometric electrical alignment test structures [1] were included. Both types were designed with different combinations of contact window size, doped region width, and voltage sensing arm spacing. One type, structures 1 through 5 and structure 8, is used to measure the misalignment between the doped region and the contact window photomask levels. This structure is illustrated in figure 1; in this and subsequent figures each level is identified as follows: doped regions are enclosed by heavy solid lines, contact areas are denoted by cross-hatched rectangles, and the metal areas are enclosed by light solid lines, and the critical dimensions are labeled. The critical dimensions of the various forms of the structure are given in table 1. The second type, structures 6 and 7, is used to measure the misalignment between the doped region and the metal photomask levels. This structure is illustrated in figure 2, and the critical dimensions are also given in table 1. Both types of structures are measured in the same way; the structure is analogous to a linear potentiometer where the mid-point of the resistor is sensed by measuring the voltage imbalance between the sliding contact and the ends of the potentiometer when a constant current is passed through the resistor. The structure is designed so that when there is perfect alignment between the two mask levels, the distances L_2 between the center of the tap and the center of the contact window opening (type 1) or the center of the metal contact arm (type 2) are equal. Then, the resistance R_{29} between pads 2 and 9 is equal to the resistance R_{93} between pads 3 and 9, and the resistance R_{65} between pads 5 and 6 is equal to the resistance R_{76} between pads 6 and 7. When the contact window opening (type 1) or the metal contact arm (type 2) is displaced from the design position, the resistances are no longer equal. The displacements in the x- and y-directions, ΔL_x and ΔL_y, are calculated from [2]

$$\Delta L_x = \frac{L_1}{2} \; \frac{R_{65} - R_{76}}{R_{12}} \tag{1}$$

and

$$\Delta L_y = \frac{L_1}{2} \; \frac{R_{93} - R_{29}}{R_{12}} \; . \tag{2}$$

Two types of visual alignment indicator test structures [1,3,4,] were also included. Structures 16 and 23, are used to measure the misalignment between the metal and doped region photomask levels while structures 17 and 24 are used to measure the metal and contact mask levels misalignment. In each of these structures, a "Vee" from one mask level is superimposed on a rectangle from a previous mask level, as shown in figures 3 through 6. The displacement of the crossing points of the Vee and the rectangle is proportional to the misalignment of the two levels and is given by

$$\Delta L = \frac{\ell_1}{\ell_2} \frac{\ell \tan\Theta}{2}, \qquad (3)$$

where ℓ_1 is the displacement of the crossing points and ℓ_2 is the separation of the leading edges of the small rectangles. Both ℓ_1 and ℓ_2 are measured by a visual technique and have arbitrary units. To relate ℓ_1 and ℓ_2 to an absolute scale, the designed separation, ℓ, between the leading edges of the small rectangles is used. For the structure in this test pattern, ℓ was chosen to be 20 μm and Θ was chosen to be 0.1 rad (5.7 deg) so that $\frac{1}{2}\ell\tan\Theta = 1$ μm, and eq (3) becomes

$$\Delta L = \frac{\ell_1}{\ell_2}, \qquad (4)$$

where ΔL is in micrometers. In any visual measurement, there is a certain amount of subjectivity. It was expected that when the structure is measured one would prefer to see the Vee part of the structure in the metal with rectangles in the oxide as in structures 16 and 17. This order was reversed in structures 23 and 24; here the metal is seen as a rectangle and the oxide contains the Vee. In experiments to compare the electrical and visual structures [1], no differences were observed for these two locations of the Vee.

Since the potentiometric electrical alignment resistor may be sensitive to several process nonuniformities, it was necessary to include several other test structures in the test pattern in order to test for these. Variations in either the sheet resistance or the width of the doped region within the test structure lead to resistance differences which will interfere with the measurement. To determine the magnitude of these variations, cross bridge sheet resistors [5] were included for the doped region, structures 9 and 10, shown in figure 7, and for the metal, structure 21, shown in figure 8. Procedures for measuring these structures and calculating sheet resistance and line width for the measurements are given in [5] which is reproduced as Appendix A.

Incomplete etching of the contact window or other metal-semiconductor contact faults lead to erroneous results. The contact resistance test structure [6] used in several previous test patterns was included to provide information on contact quality. This structure is shown in figure 9. Because the structure is affected by contact window geometry, five versions (structures 11 through 15) which repeat the various geometries of the contact window in the electric alignment structure were included in the test pattern. Use of this structure is described in [6] which is reproduced as Appendix B. Initial experiments have indicated that large variations in the measured contact resistance are due to aluminum and silicon incompletely alloying over the entire contact window.

The isolation diode, structure 22, shown in figure 10, is composed of interdigitated doped regions of opposite conductivity type to the substrate which therefore form *pn* junctions with the substrate. If a potential is applied between the two contact pads, the presence of a significant current implies either surface leakage or poor isolation of the doped region both of which may interfere with measurements.

3. DESCRIPTION OF THE TEST PATTERN

The various structures were assembled into a rectangle 2.44 mm wide and 1.60 mm high. The pattern is arranged modularly with six 2 by 10 columns of probe pads which contain the various electrically measured test structures. The visual alignment indicators are placed in two skipped columns as shown in the computer drawing of the complete test pattern in figure 11. As in the drawings of the individual test structure, each level of the test pattern is identified as follows: doped regions enclosed by heavy solid lines, contact window areas denoted by cross hatched rectangles, and the metal areas enclosed by light solid lines. This drawing contains the digitized rectangles for computer-controlled pattern generation. Two types of fabrication alignment marks are included in the pattern: square (structure 19) and plus sign (structure 20). A photomicrograph of a fabricated die is shown in figure 12. The doped regions appear as black regions, the contact opens as gray regions enclosed by black lines, and the metallizations are white.

The test pattern was implemented in a three-level mask set intended for use with positive photoresist. Therefore, the doped region and contact window masks are dark field and the metal mask is light field. The pattern was laid out in metric units with a computer-aided design system which results in an Electromask* compatible magnetic tape which contains the information necessary for a computer controlled pattern generator to fabricate the three 10X reticles. On this

*This instrument is identified in this publication for the purpose of providing a complete description of the work performed. In no case does such identification imply recommendation or endorsement by the National Bureau of Standards nor does it imply the item identified is necessarily the best available for the purpose.

tape,[+] level 1, for the doped regions, is composed of 490 rectangles; level 2, for contact windows, 380; and level 3, for the metal level, 575.

4. USE OF THE TEST PATTERN

The individual electrical alignment test structures can be incorporated into any test pattern to provide local information about mask registration. Working masks have been made in which the entire pattern has been stepped and repeated on 2.54-mm (100-mil) centers to completely cover a wafer.[†] Vector maps from measurements can be used to evaluate [1,7,8,9] the misalignment which results from photomask generation, photomask exposure, and other fabrication processes. Preliminary results of measurements of mask registration using this test structure have been reported elsewhere [1].

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[+] Contact the Electron Devices Division, National Bureau of Standards, Washington, D.C. 20234 for information on availability of this tape.

[†] To be able to test dice on a wafer using a certain metric or an English automatic prober, the dice must be centered on multiples of 1.27 mm (50 mil). Since the minimum step on the metric prober is 10 μm and on the English prober 2.54 μm (0.1 mil), the minimum step common to both is 1.27 mm or 50 mil.

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Table 1. Test Structure List

Structure Number	Test Structure Description	Specification/Notes W, C_1, C_2, L_1, L_2, M(μm)	Page
1	Contact-to-doped-region electrical alignment resistor	18, 6, 6, 122, 61, -	9
2	Contact-to-doped-region electrical alignment resistor	24, 6, 6, 122, 61, -	9
3	Contact-to-doped-region electrical alignment resistor	24, 12, 6, 122, 61, -	9
4	Contact-to-doped-region electrical alignment resistor	24, 6, 12, 122, 61, -	9
5	Contact-to-doped-region electrical alignment resistor	24, 12, 12, 122, 61, -	9
6	Metal-to-doped-region electrical alignment resistor	24, 12, 16, 122, 61, 8	10
7	Metal-to-doped-region electrical alignment resistor	24, 12, 24, 122, 61, 8	10
8	Contact-to-doped-region electrical alignment resistor	18, 6, 6, 80, 80, -	9
9	Doped-region cross-bridge sheet resistor	18, -, -, 200, 40, -	15
10	Doped-region cross-bridge sheet resistor	24, -, -, 190, 44, -	15
11	Metal-to-doped-region contact resistor	18, 6, 6, -, -, -	17
12	Metal-to-doped-region contact resistor	24, 6, 6, -, -, -	17

Structure Number	Test Structure Description	Specification/Notes W, C_1 C_2, L_1, L_2, M(μm)	Page
13	Metal-to-doped-region contact resistor	24, 6, 12, -, -, -	17
14	Metal-to-doped-region contact resistor	24, 12, 6, -, -, -	17
15	Metal-to-doped-region contact resistor	24, 12, 12, -, -, -	17
16	Metal-to-doped-region visual alignment indicator	Vee in metal level ℓ = 20 μm, Θ = 5.7 deg	11
17	Metal-to-doped-region visual alignment indicator	Vee in metal level ℓ = 20 μm, Θ = 5.7 deg	13
18	NBS-15 logo		
19	Square mask alignment markers		21
20	Plus sign mask alignment markers		22
21	Metal cross bridge sheet resistor	8, -, -, 200, 40, -	16
22	PNP isolation diode		18
23	Metal-to-doped-region visual alignment indicator	Vee in doped region level ℓ = 20 μm, Θ = 5.7 deg	12
24	Metal-to-contact visual alignment indicator	Vee in contact level ℓ = 20 μm, Θ = 5.7 deg	14

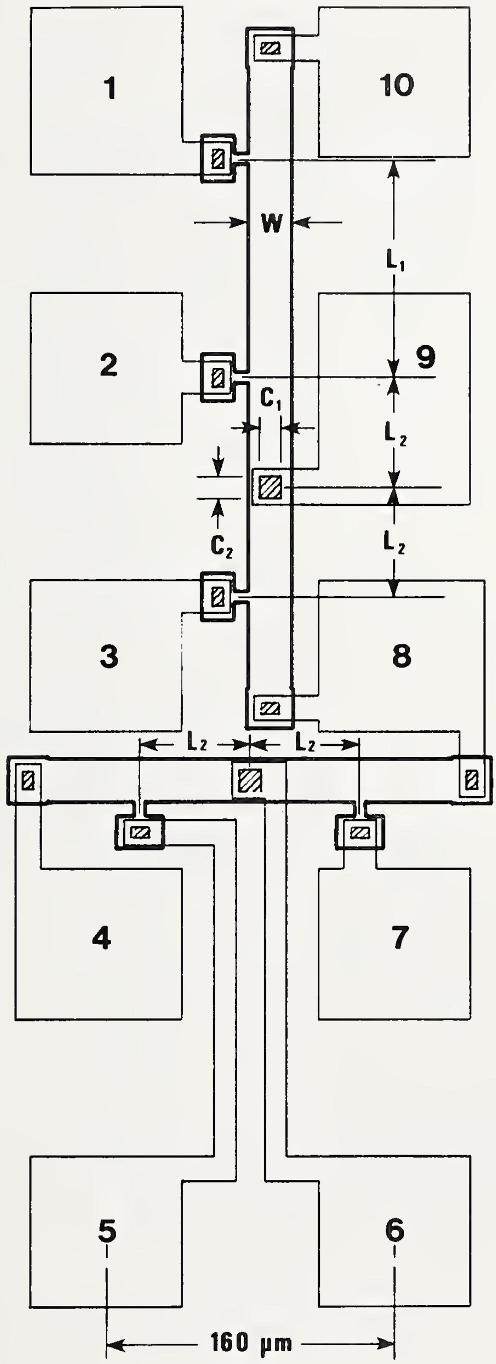

Figure 1. Contact-to-doped region electrical alignment resistor (structures 1,2,3,4,5 and 8).

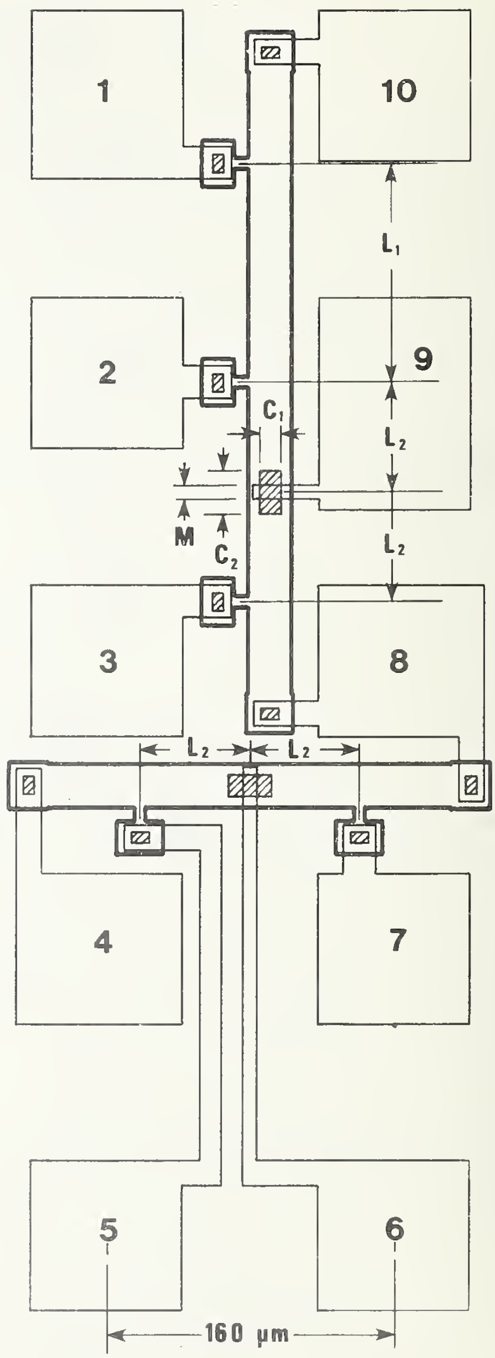

Figure 2. Metal-to-doped region electrical alignment resistor (structures 6 and 7).

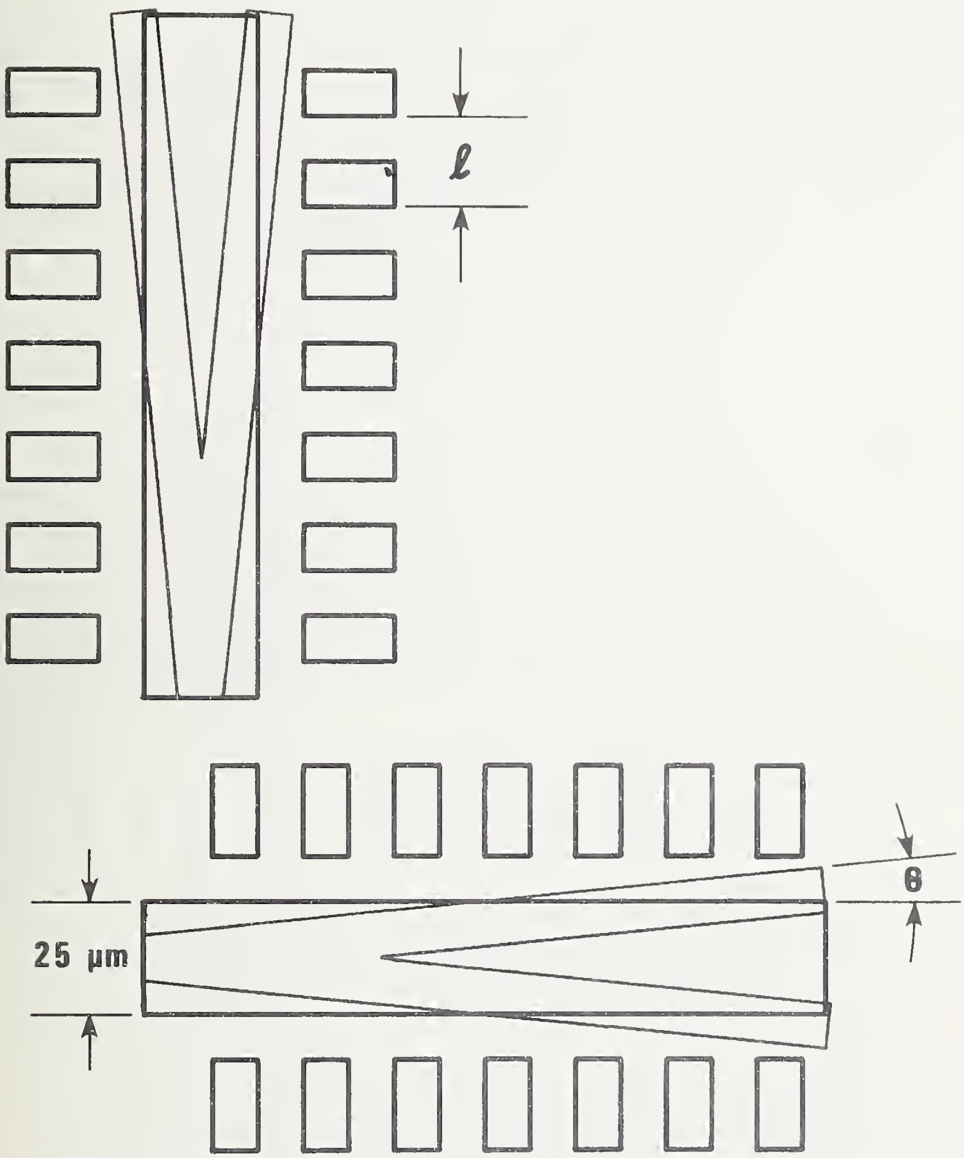

Figure 3. Metal-to-doped region visual alignment indicator (structure 16).

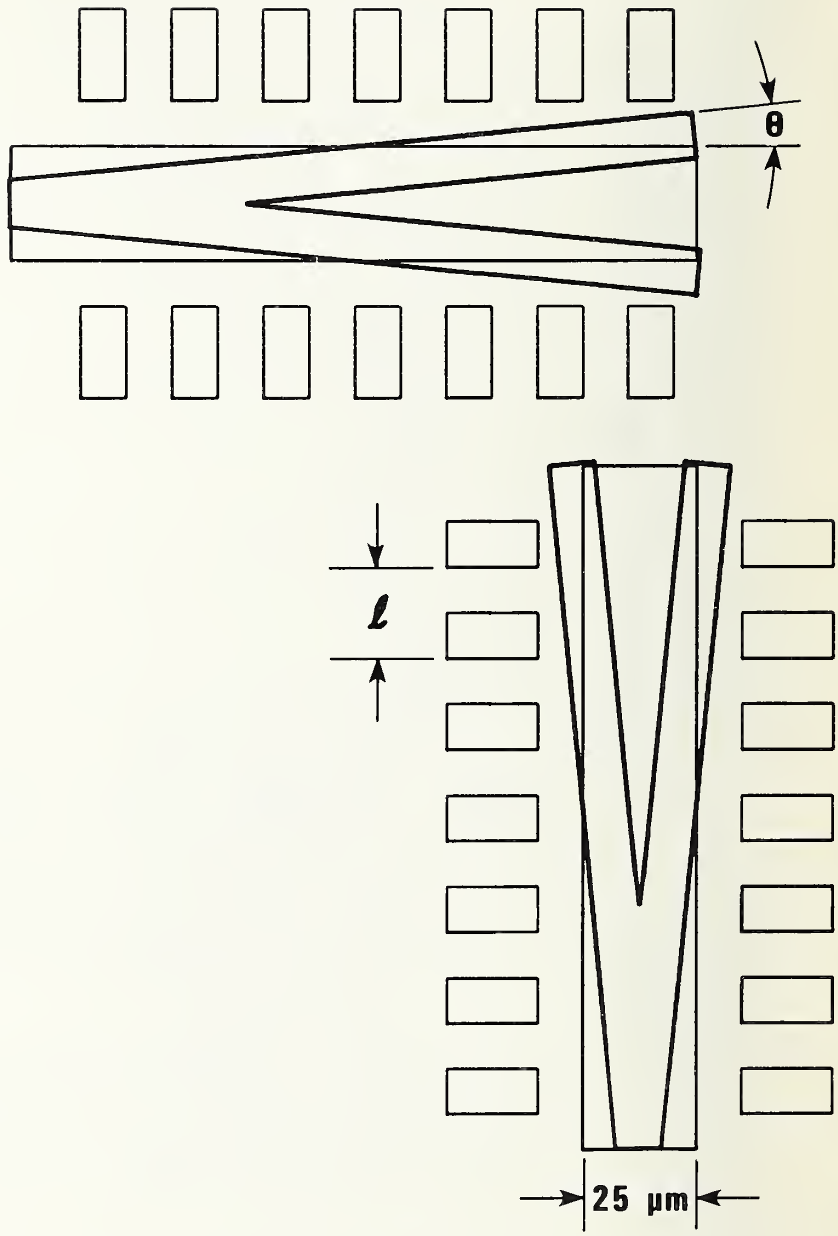

Figure 4. Metal-to-doped region visual alignment indicator (structure 23).

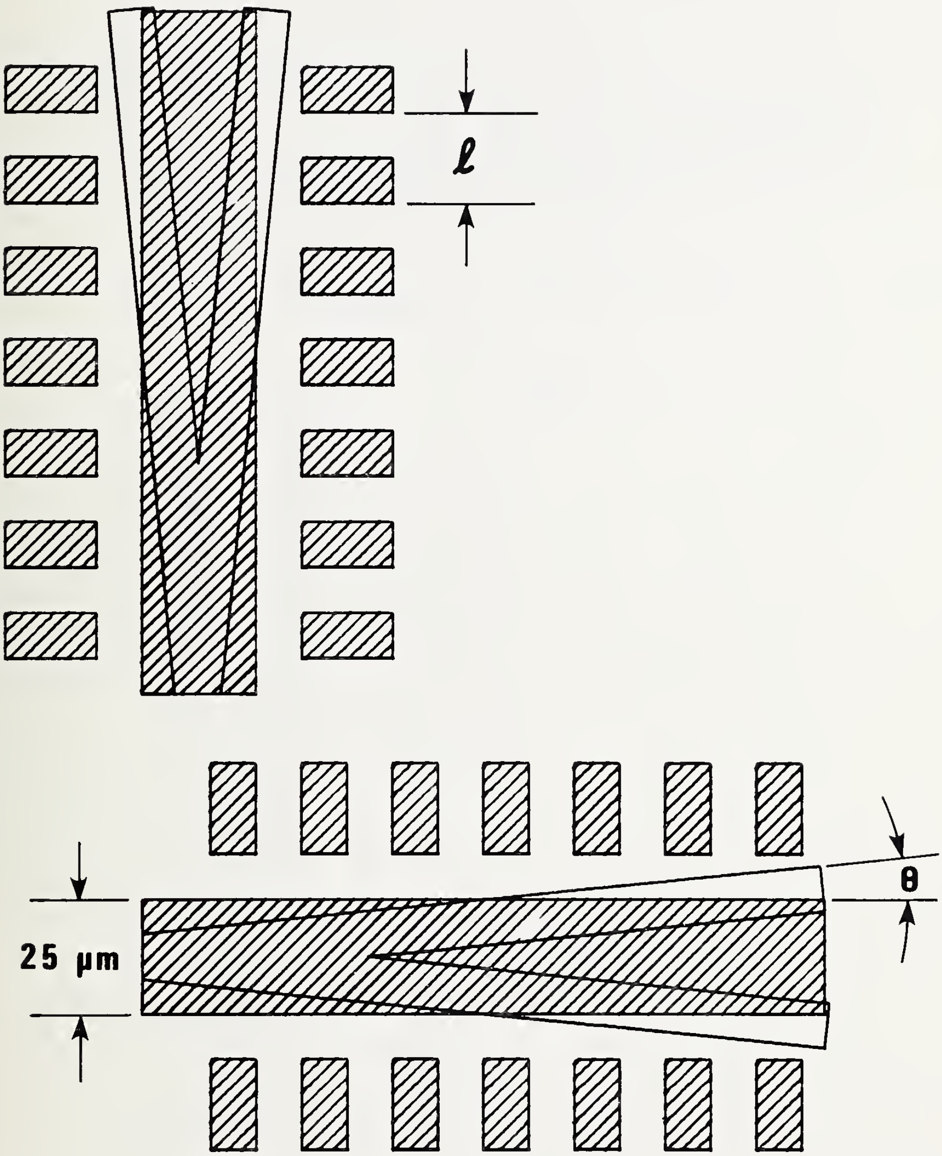

Figure 5. Metal-to-contact visual alignment indicator (structure 17).

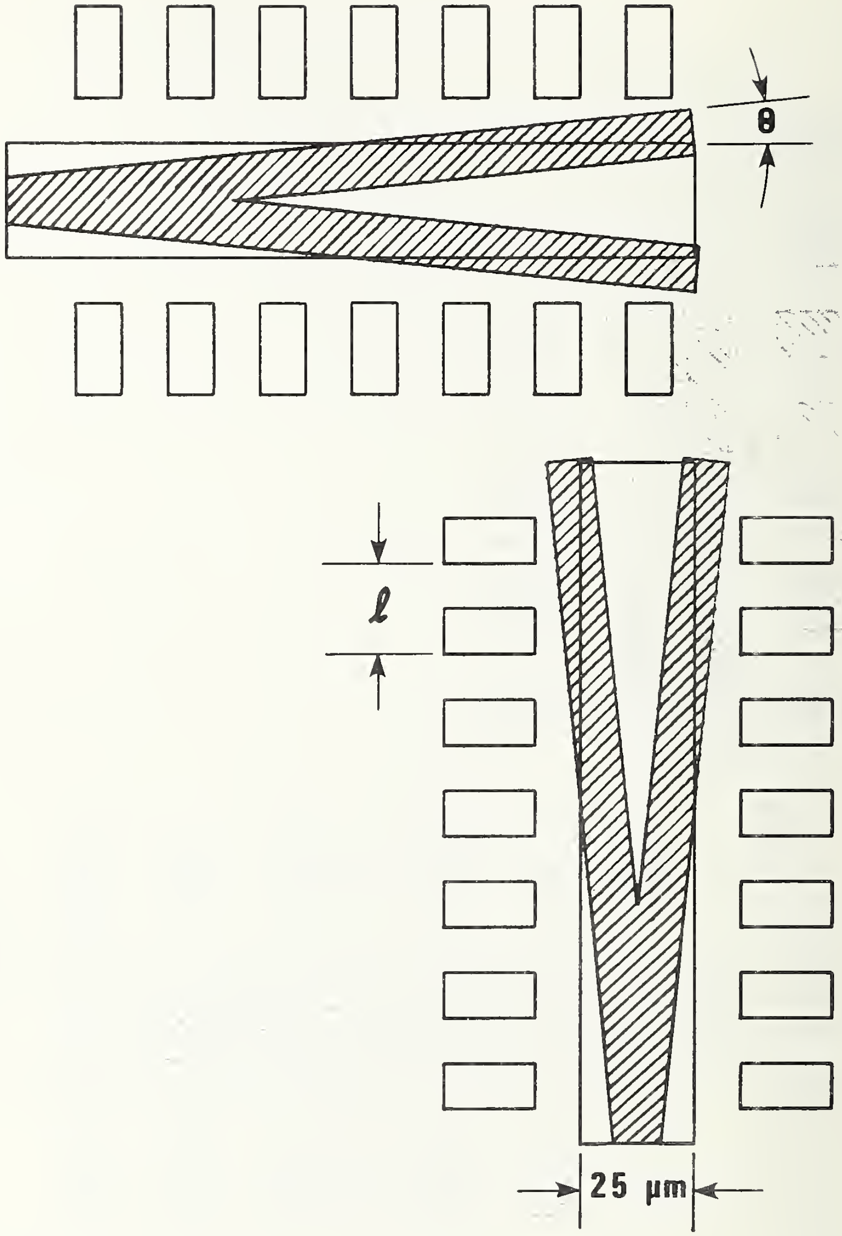

Figure 6. Metal-to-contact visual alignment indicator (structure 24).

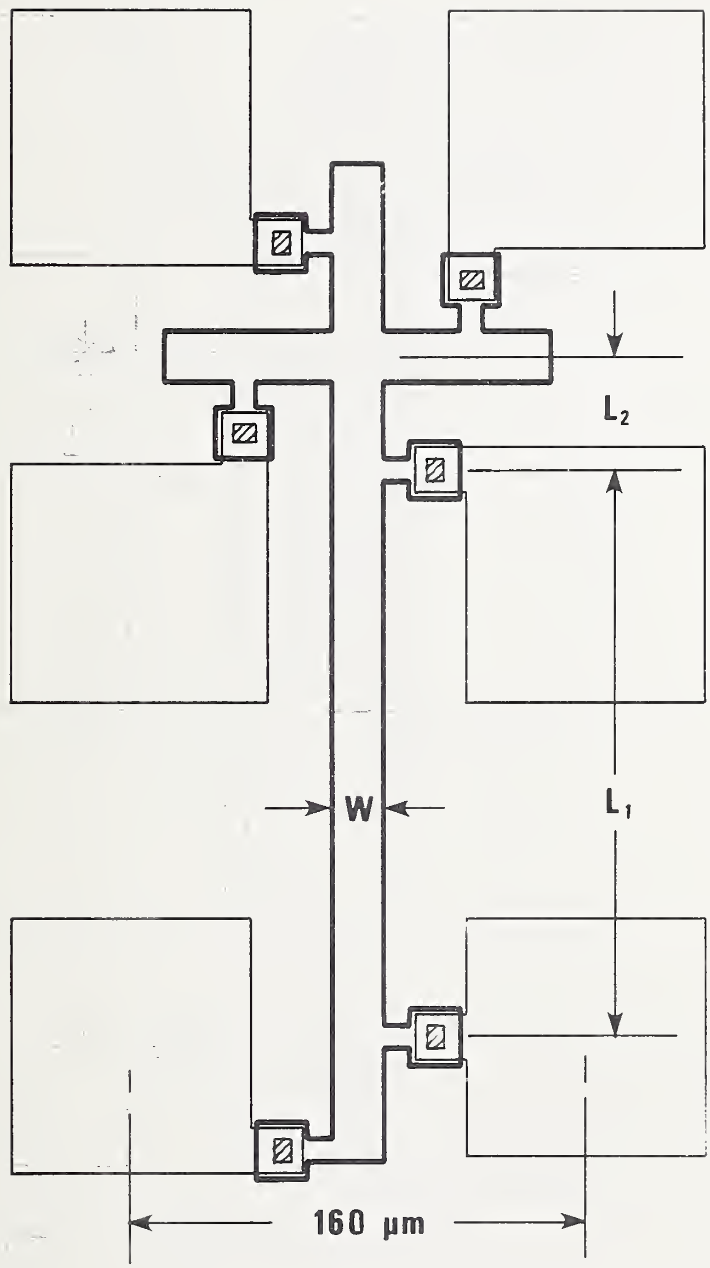

Figure 7. Doped region cross bridge sheet resistor (structures 9 and 10).

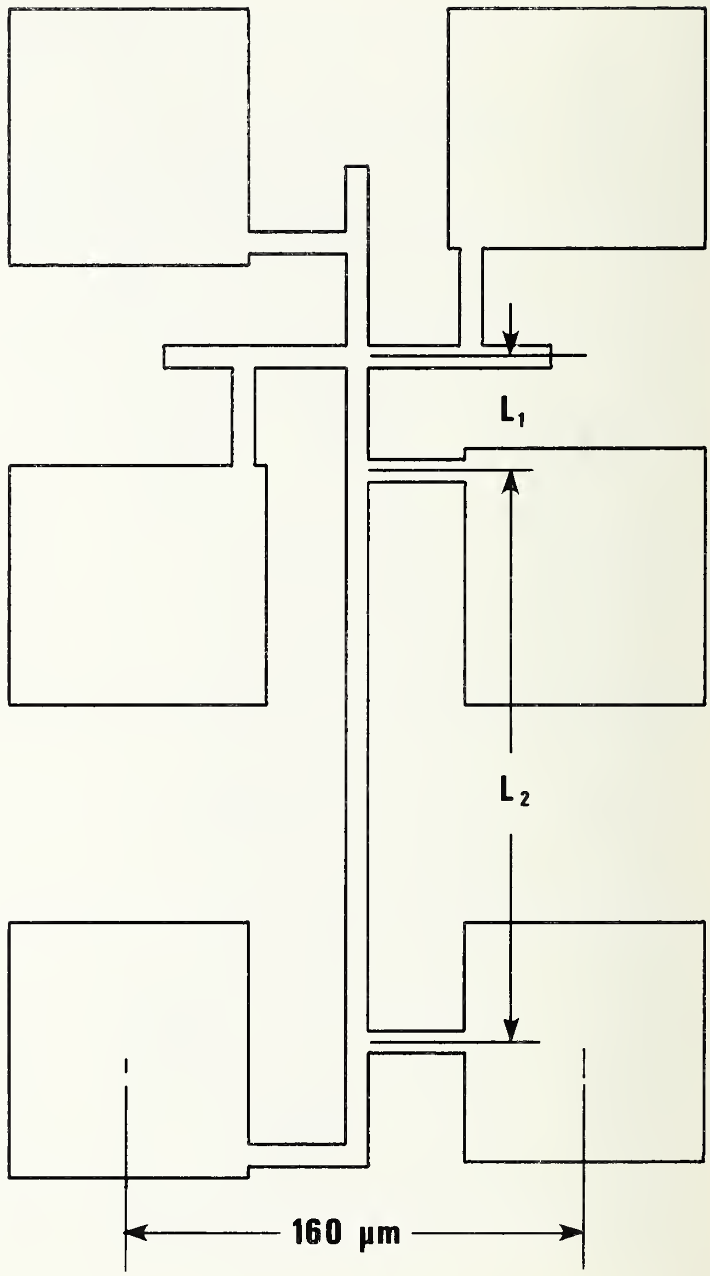

Figure 8. Metal cross bridge sheet resistor (structure 21).

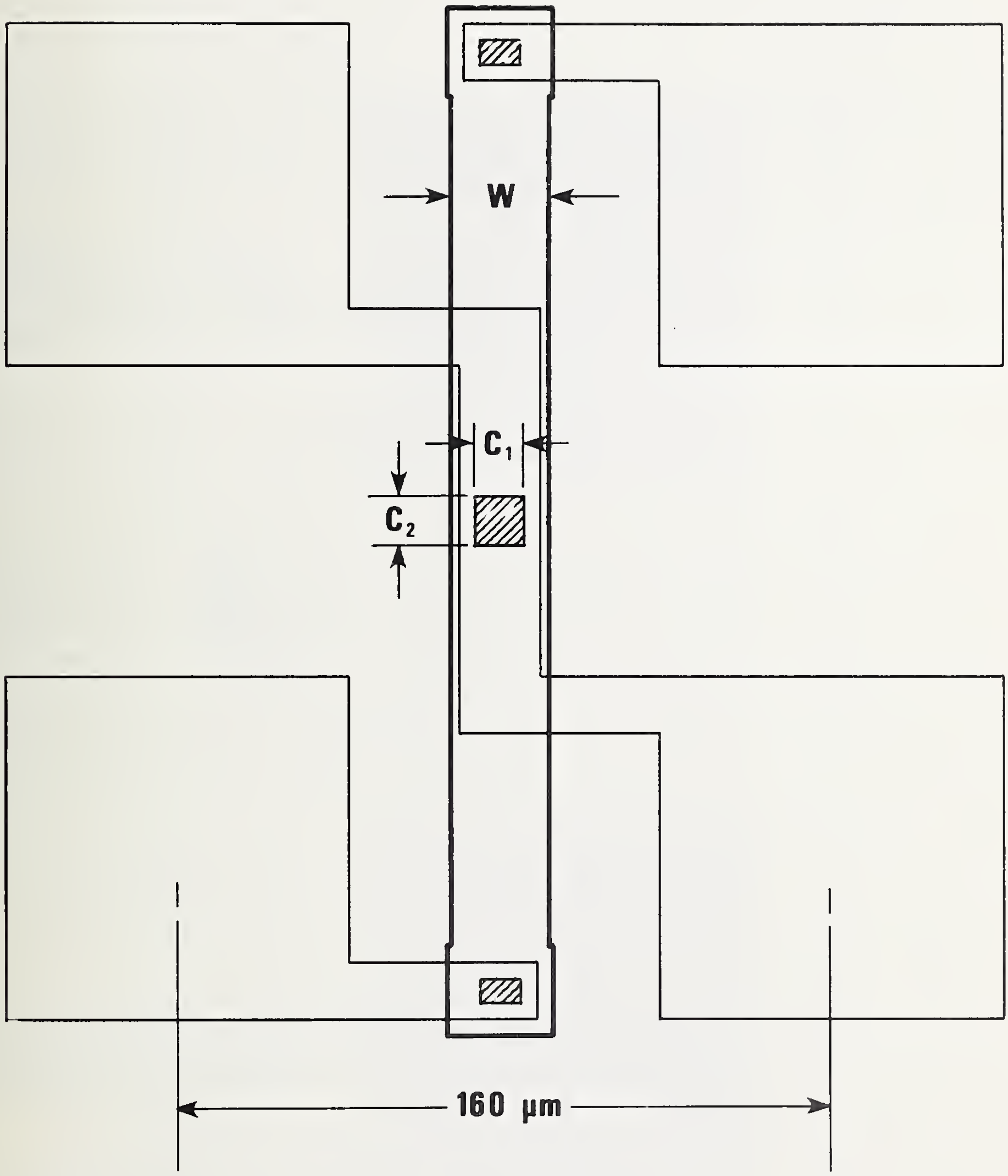

Figure 9. Metal-to-doped region contact resistor (structures 11, 12, 13, 14 and 15).

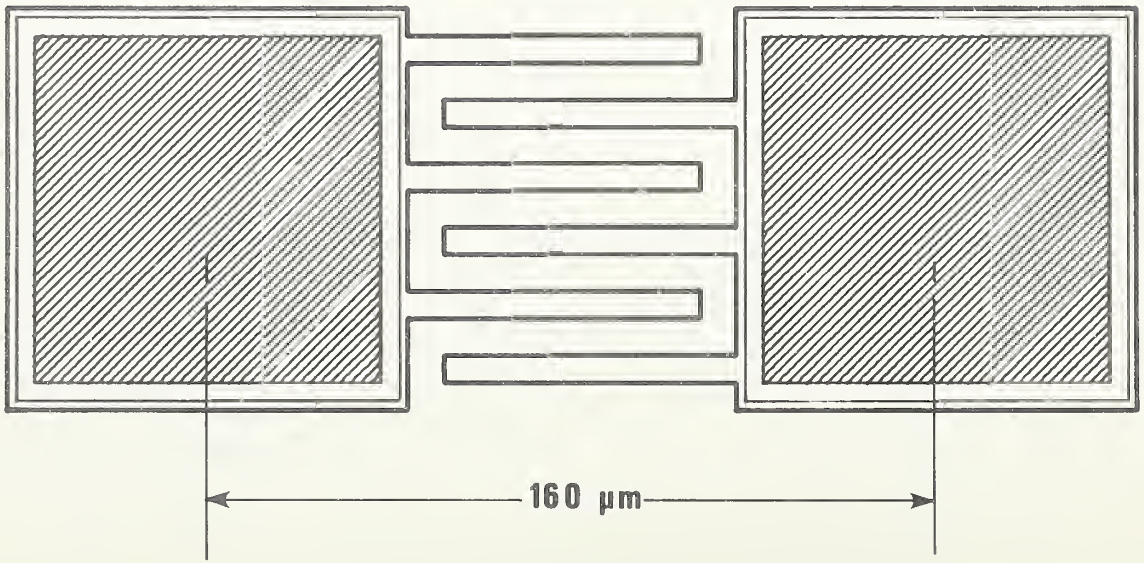

Figure 10. PNP isolation diode (structure 22).

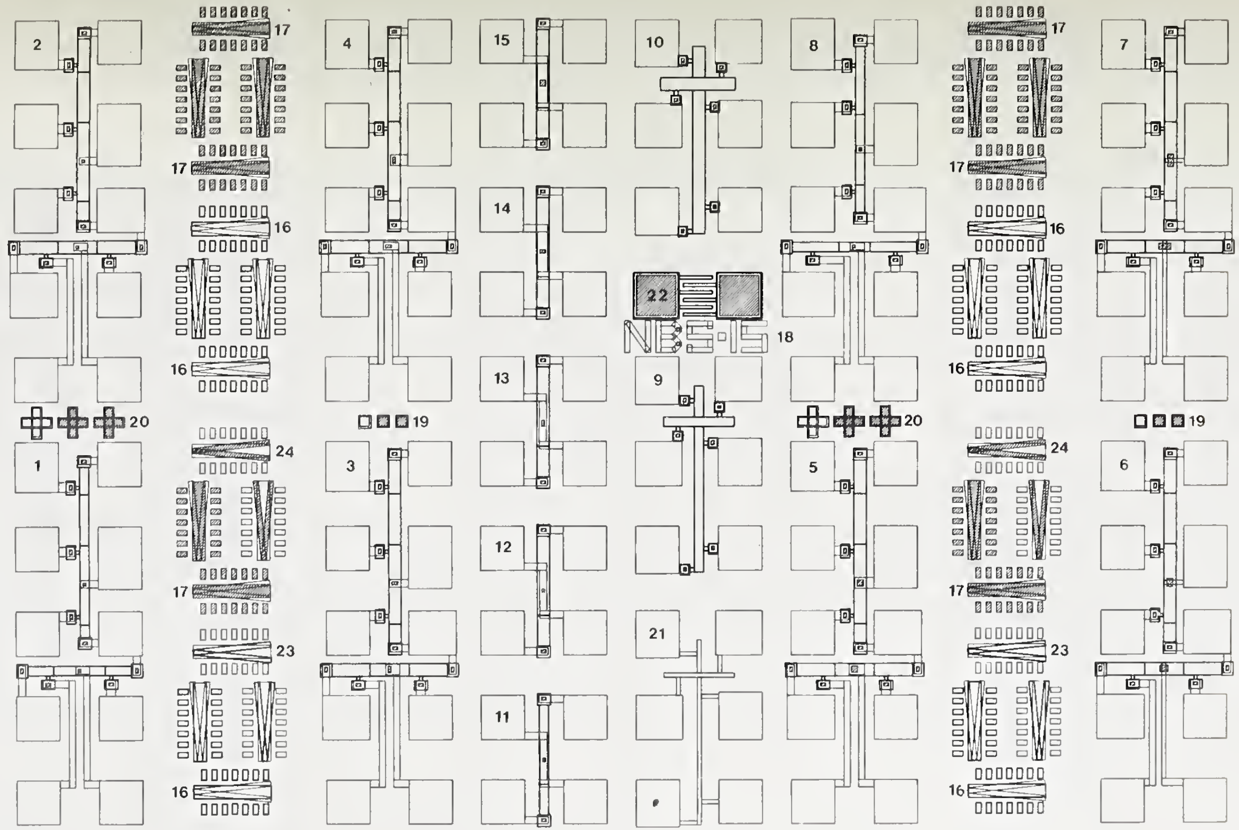

Figure 11. Computer drawing of NBS-15 test pattern with structures numbered.

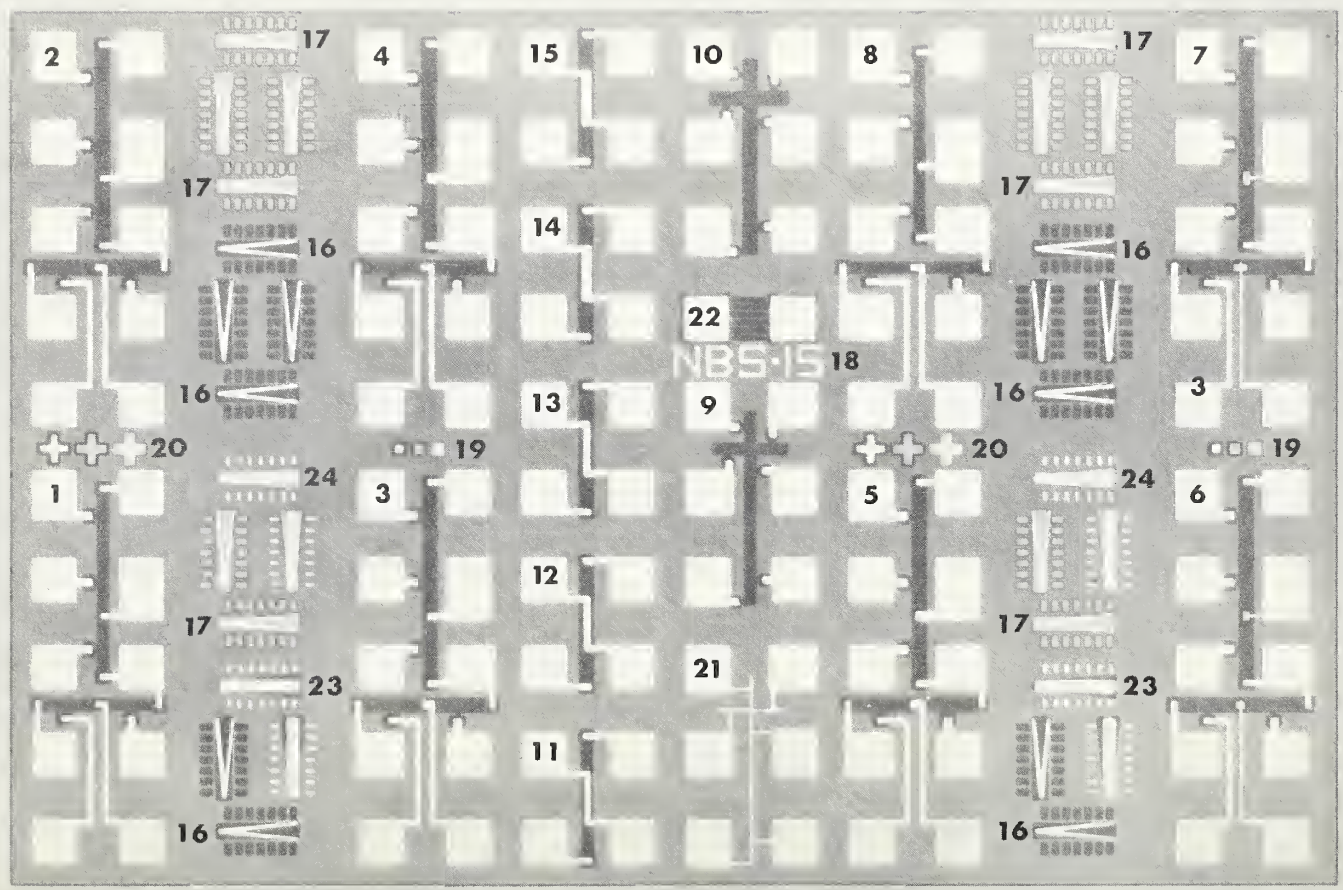

Figure 12. Photomicrograph of NBS-15 test pattern. (The doped regions are black, the contact level is gray outlined by black lines, and the metallization is white. Contacts under metal are not clearly visible.)

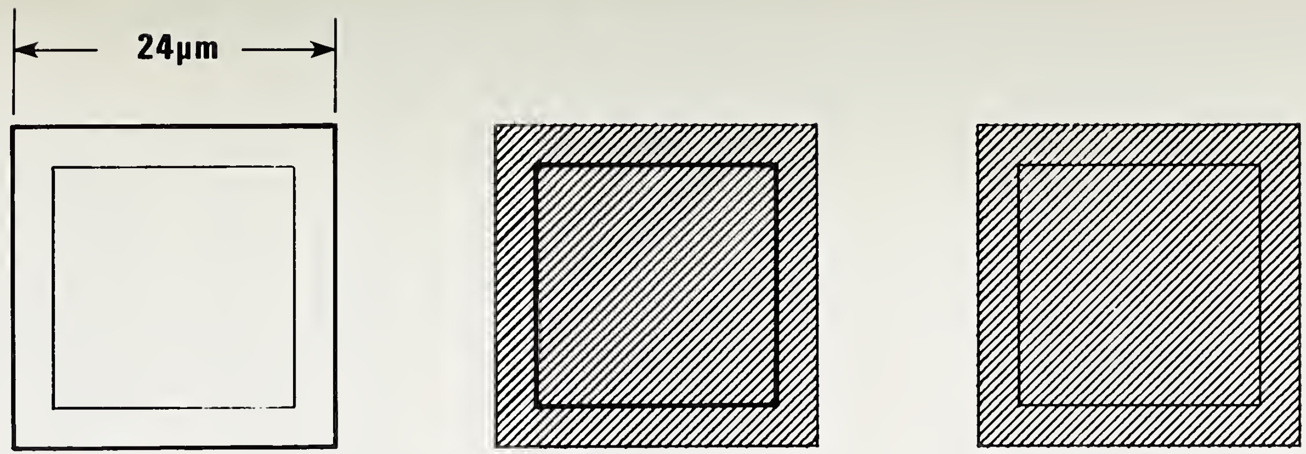

Figure 13. Square mask alignment markers (structure 19).

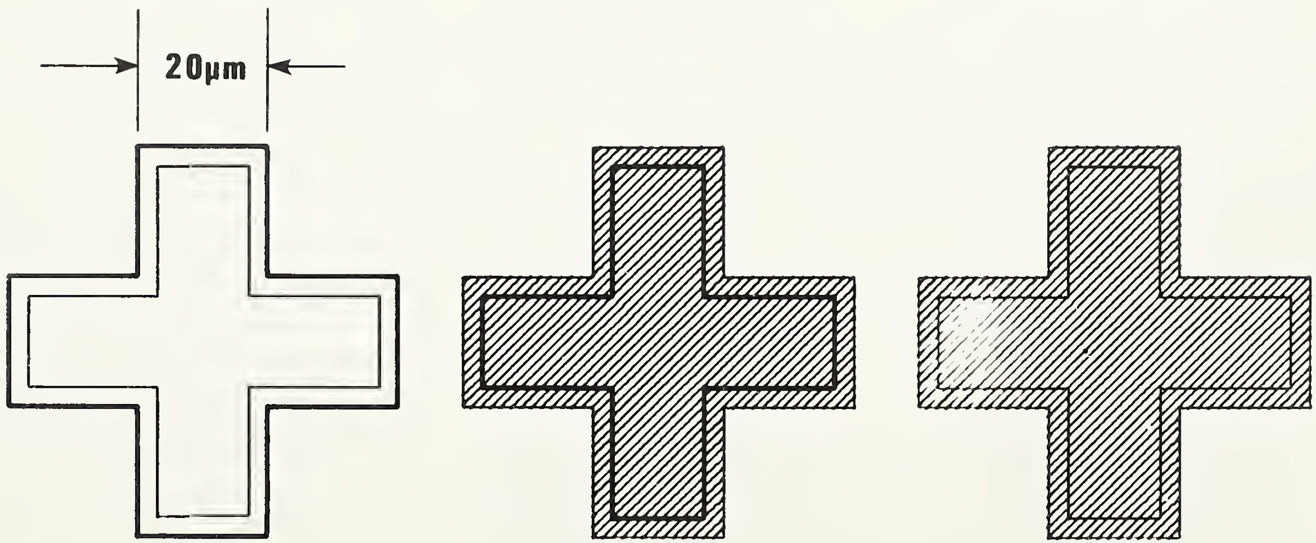

Figure 14. Plus sign mask alignment markers (structure 22).

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Bridge and van der Pauw Sheet Resistors for Characterizing the Line Width of Conducting Layers

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ABSTRACT

It is shown that the line width of conducting layers can be computed from simple d-c electrical measurements made on bridge and van der Pauw shaped test structures. A compact six-contact, cross-bridge sheet resistor test structure was developed to make this measurement directly. Line widths measured on boron nitride diffused layers indicate that the method is sensitive to width variations of the order of ± 0.1 μm (± 4 μin.)

The measurement of line widths in the microelectronic industry is needed for the process control and design of integrated circuit components. For process control, line-width measurements are useful in monitoring the many etching processes which define the width of oxide windows and conducting layers. In circuit design, the value of diffused or implanted resistors is determined in part by the line width of the conducting layer.

Conventional methods for measuring the line width include both optical (1) and electrical techniques.

* Electrochemical Society Active Member.
Key words: cross-bridge structure, diffused layer, line width, process control, sheet resistance.

The electrical techniques commonly employ the double-bridge method (2) which requires the fabrication of two bridge structures of different width. Since this measurement technique is a differential-type method, it suffers from errors in taking the difference of large numbers.

An alternative to these methods is the determination of line widths using a bridge structure (3) in combination with a van der Pauw test structure (4). The width of the bridge structure is calculated from measurements of its resistance along with knowledge of the length between the voltage taps and the sheet resistance value obtained from the van der Pauw structure. The advantage of these vehicles is that they can be combined into one compact structure with the same line width, which means that the conductivity of the composite is more uniform than would generally be true for separate structures. In addition, the computation of the line width does not depend on the difference of large numbers; however, the analysis of the van der Pauw structure requires the measurement of low voltages, usually in the range from 1 to 10 mV. This is not a problem for laboratory-based instrumentation but precludes the use of those integrated circuit testers which do not measure these low voltages.

Test Structure Design and Fabrication

Line drawings of the test structures used in this study are shown in Fig. 1-4. Metallized contact to diffused regions is shown by the crosshatched areas. Structures 3.22 and 3.28 were fabricated as a part of test pattern NBS-3 (5) and the structures 7.18 and 7.23 were fabricated as a part of test pattern NBS-7 (6). The dimensions for these structures are listed in Table I.

The bridge test structure shown in Fig. 1 was designed in accordance with the ASTM standard (3) which requires that $W_m \geqq 3D_m$ and $B_m \geqq 2W_m$. In addition the lateral diffusion and overetch effects were minimized by requiring that $A_m \geqq 5X_j$ and $C_m \geqq 5X_j$, where X_j is the junction depth. The subscript m indicates a parameter referred to photomask dimensions.

The offset quadrate-cross test structure shown in Fig. 2 was designed to eliminate the contact shorting

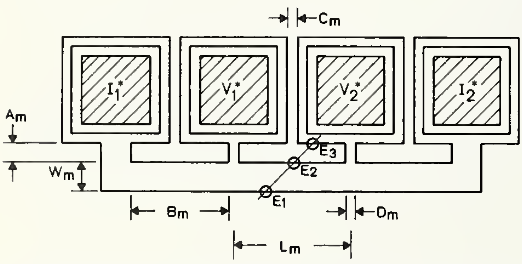

Fig. 1. Bridge sheet resistor test structure (3.28). The edges E_1, E_2, and E_3 are used to determine the width from optical photomicroscopic measurements.

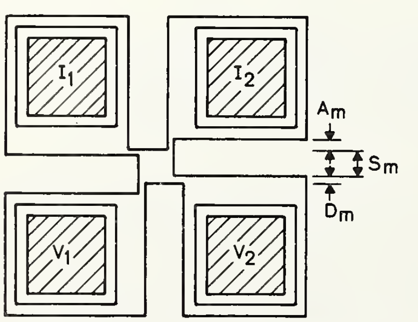

Fig. 2. Offset quadrate-cross test structure (3.22)

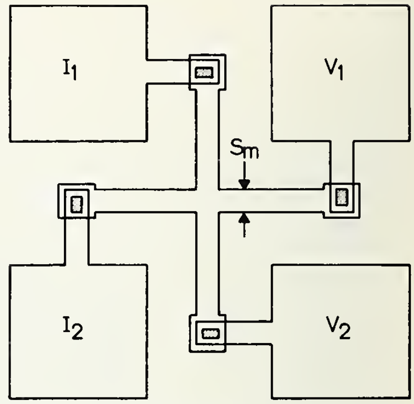

Fig. 3. Greek-cross sheet resistor test structure (7.18)

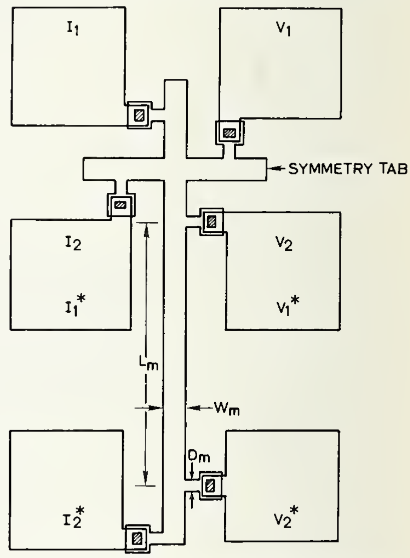

Fig. 4. Cross-bridge sheet resistor test structure (7.23)

correction factor (7) associated with the van der Pauw equation. For this structure where $A/S = 0.33$ and $D/S = 0.17$, the correction factor is much less than 0.1% and may be neglected. Likewise, the Greek-cross test structure shown in Fig. 3 was designed so that the arm length is greater than the arm width which means that the contact shorting correction factor associated with this structure also can be neglected (7).

The cross-bridge structure shown in Fig. 4 is a combination of the bridge structure shown in Fig. 1 and

Table I. Test structures

Number	Figure	Type	Photomask dimensions µm (mil)
3.28	1	Bridge	A_m = 25.4 (1.00)
			B_m = 127.0 (5.00)
			C_m = 12.7 (0.50)
			D_m = 12.7 (0.50)
			L_m = 139.7 (5.50)
			W_m = 38.1 (1.50)
3.22	2	Offset quadrate cross	A_m = 25.4 (1.00)
			D_m = 6.4 (0.25)
			S_m = 38.1 (1.50)
7.18	3	Greek cross	S_m = 14.0 (0.55)
7.22	4	Cross bridge	D_m = 8 0 (0.31)
			L_m = 200.0 (7.87)
			W_m = 16.0 (0.63)

the Greek-cross structure shown in Fig. 3. The bridge part was designed in accordance with the ASTM standard (3) except that $W_m = 2D_m$. The cross part was designed to eliminate the contact shorting correction factor (7). In order to preserve the symmetry of the cross, symmetry tabs were introduced at the ends of the arms denoted I_1, I_2, and V_1. These tabs are intended to compensate for the extension of the structure along the arm denoted V_2.

The test structures shown in Fig. 1-4 were fabricated by photolithographic processes using contact printing and an n-p-n transistor process. Both emitter and base sheet resistors were fabricated. The base sheet resistors, which were used to obtain the results reported in this study, were fabricated on n-type, (111)-oriented silicon substrates on which a 300 nm thick oxide was grown in steam at 1100°C. Diffusion windows were etched in the oxide. The boron nitride predeposition diffusion was at 965°C in dry nitrogen for about 30 min. After a deglaze in 10% hydrofluoric acid solution, the base was diffused at 1100°C for 18 min in wet oxygen, followed by 40 min in dry oxygen, followed by 15 min in dry nitrogen. This creates over the base regions a 350 nm thick oxide that masks the subsequent emitter diffusion. The final high temperature steps occurred at 1025°C for 20 min and at 925°C for 45 min. The structures were complete after opening the contact windows and patterning the aluminum metallization. The base sheet resistance was nominally 200 Ω/□. Test structures 3.22 and 3.28 were fabricated in wafers numbered 28, 29, and 30; the junction depth was 2.1 μm. Structures 7.18 and 7.23 were fabricated in a 9 Ω-cm wafer, D8.8 Ph-1; the junction depth was 1.6 μm.

Electrical Measurements

The electrical measurements utilized the d-c four-probe method where current was forced between two contacts to the resistor and the voltage was measured between two additional contacts. The current from a constant current source was determined either from the voltage drop across a standard resistor or was assumed to be within the stated accuracy. Current reversal was achieved by switching the current through a mechanical switch or relay to ensure that the magnitude of the reverse current equals that of the forward current. The magnitude of the current was chosen so that the measured voltage was between 0.5 and 10 mV. The substrate was allowed to float electrically during these measurements.

The line width is determined from measurements on the bridge structure in combination with measurements on the van der Pauw structure. The sheet resistance is determined from the van der Pauw structure by utilizing probe pads labeled I_1, I_2, V_1, and V_2 shown in Fig. 2, 3, or 4 and is calculated from the van der Pauw formula (4)

$$R_s = \pi R(\pm I)/\ln 2 \quad [1]$$

where $R(\pm I)$ is the incremental resistance determined from the current and voltage measurements for both directions of current and both contact orientations; see preceding paper (8). The parameter f which appears in the complete form of the van der Pauw formula is assumed to be unity in this study since the asymmetry factor, F_A, was much less than 10% (8).

The line (or window) width is determined by utilizing probe pads labeled I_1^*, I_2^*, V_1^*, and V_2^* shown in Fig. 1 and 4. The effective width, W_e, of the current-carrying channel is calculated from

$$W_e = R_s L_m / R^*(\pm I) \quad [2]$$

where R_s is determined from Eq [1] and L_m is the distance between voltage taps as determined from the photomask. The incremental resistance determined from measurement for both forward $(+I)$ and reverse $(-I)$ currents is given by

$$R^*(\pm I) = [V^*(+I) - V^*(-I)]/[I^*(+I) - I^*(-I)] \quad [3]$$

For measurements made in the forward current mode, the current $I^*(+I)$ is passed into I_1^* and out of I_2^* where both $I^*(+I)$ and $V^*(+I) = V_1^*(+I) - V_2^*(+I)$ are positive quantities. For measurements made in the reverse current mode, both $I^*(-I)$ and $V^*(-I)$ are negative quantities. The above expressions assume that the voltage taps do not significantly perturb the current flow in the current-carrying channel.

If the test structure is a diffused layer then the effective width is

$$W_e = W_m + \alpha X_j + W_{oe} \quad [4]$$

where W_m is the width determined from the photomask, W_{oe} is the incremental change in the width due to photolithographic effects and overetching, and αX_j is the effective incremental change in the width due to lateral diffusion where X_j is the junction depth and α is the lateral diffusion factor (9). Since the lateral diffusion cannot be observed from the top surface of the structure, the optically observable line width is

$$W = W_e - \alpha X_j = W_m + W_{oe} \quad [5]$$

These quantities are shown in detail in Fig. 5.[1]

Line-Width Measurements

Line widths for the bridge structure shown in Fig. 1 were measured as a function of position across a wafer by both electrical and optical techniques. In order to compare the two techniques, the factor αX_j, with α assumed to have the value 0.3 (9) and $X_j = 2.1$ μm for wafers 28, 29, and 30, was subtracted from the effective line width, W_e, which was evaluated from the electrical measurements with the use of Eq. [2]. In Fig. 6 the sensitivity of the method to etch time is illustrated by an experiment where the base diffusion

[1] If the test structure is a deposited layer, the effective width, which is the same as the optically observable width, W, is $W_e = W_m - W_{oe}$.

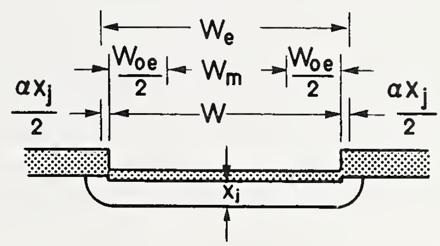

Fig. 5. Cross-sectional view of a diffused region showing various dimensions. To account for lateral diffusion effects, the width of the conducting channel is increased by an amount αX_j where the conductivity in this region is the same as in the main channel.

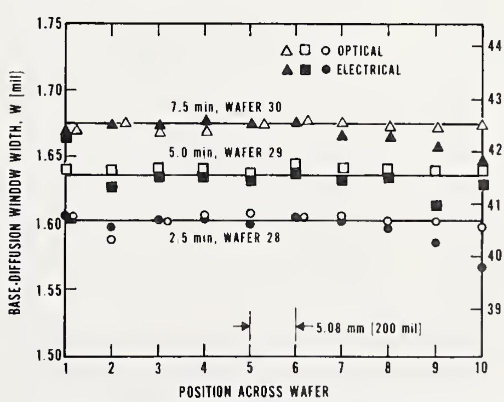

Fig. 6. Width of the base diffusion window as measured electrically and from photomicrographs along the diameter of wafers etched for different times.

window was etched for a different time on each of three wafers. The measurements demonstrate the effect of increased etch time on the window width.

The optical measurements were made directly on photomicrographs of various bridge test structures. An optical microscope with a 40× objective was operated in the dark field mode to obtain photomicrographs. The magnification as measured on the photomicrograph was 585×. The method used to determine the line width is illustrated by the points labeled E_1, E_2, and E_3 shown in Fig. 1. The distance between edges E_1 and E_3 is assumed to be unaffected by the photolithographic processes or the etch times. This distance was taken from the nominal photomask dimension and for structure 3.28 is 63.5 ± 1.3 μm (2.50 ± 0.05 mils). The distance between edges E_1 and E_2 corresponds to the optically observable width. In measuring this width a scale was placed on the photomicrograph at a convenient angle such that the distance between E_1 and E_3 was a convenient multiple of the actual dimension. The distance between edges E_1 was read directly from the scale. The estimated repeatability of both the electrical and optical line-width measurements was ±0.05 μm (±2 μin.).

The results obtained from the photomicrographs and shown in Fig. 6 compare favorably with the values obtained from the electrical measurements and in all cases the values are larger than the measured photomask width, W_m = 39.2 ± 0.3 μm (1.545 ± 0.01 mils). Sheet resistance values are typically more uniform in the center of a wafer than at the periphery. The fact that the bridge and van der Pauw resistors are located about 50 mils apart on the test pattern would affect the agreement between the electrical and optical measurements more at the edge of the wafer. The results from the center of the wafer illustrate that the electrical width measurements are sensitive to width changes of the order of ±0.1 μm (±4 μin.).

Line widths were also measured with the use of the cross-bridge test structure shown in Fig. 4. Before computing the line width it is necessary to verify that the sheet resistance is correctly determined from the cross-bridge structure. This demonstration is shown in Fig. 7 where the sheet resistance from adjacent Greek-cross (7.18) and cross-bridge (7.23) structures are compared. The results shown in Fig. 7 were analyzed by the least squares method where the slope of the line is 0.98 and the intercept is 2.9 Ω/□. The standard deviation for these measurements is 0.7% which means that sheet

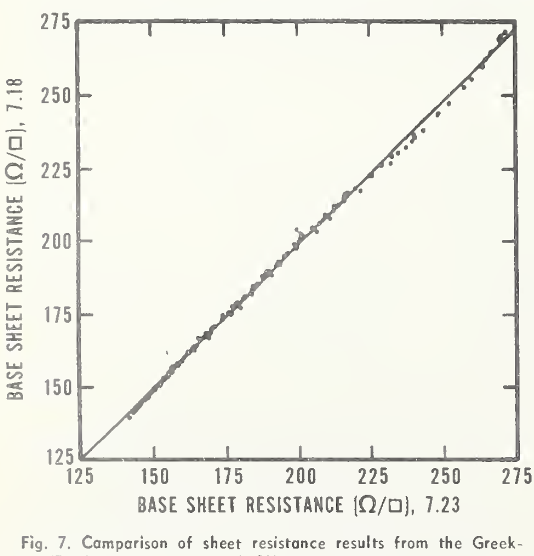

Fig. 7. Comparison of sheet resistance results from the Greek-cross (7.18) and cross-bridge (7.23) test structures.

Table II. The mean and standard deviation of various sheet resistor factors (in percent)

Structure number	F_0	F_L	F_A
7.18	0.133 ± 0.050	−0.011 ± 0.031	−0.55 ± 0.65
7.18*	1.39 ± 0.39	−0.005 ± 0.007	+0.13 ± 1.38
7.23	0.141 ± 0.050	−0.011 ± 0.010	−1.48 ± 0.72
7.23*	0.59 ± 0.11	−0.019 ± 0.006	−1.00 ± 1.21

* Data on structures designated by an * were obtained with an automated data acquisition system.

resistance values can be adequately determined from the cross-bridge test structure.

Other comparisons between the Greek-cross (7.18) and the cross-bridge (7.23) test structures are listed in Table II. The factors F_0, F_L, and F_A listed in Table II are defined in the preceding paper (8). The offset factors, F_0, measured with an automated data acquisition system are significantly larger, because of thermal voltages in the relay scanners, than those measured on a system where the digital voltmeter was connected directly to the voltage contacts. The linearity factors, F_L, are quite small being less than 0.02% which indicates that the conduction mechanism in these test structures is ohmic. As expected, the asymmetry factors, F_A, indicate that the Greek cross (7.18) is more symmetrical than the cross bridge (7.23); however, since F_A << 10%, the van der Pauw formula can be used without correction to compute the sheet resistance.

As an example of how electrical line width measurements can be utilized in process control, wafer maps of sheet resistance and effective line width W_e from Eq. [2] as determined from measurements on the cross bridge (7.23) are shown in Fig. 8. Each wafer map is divided into five increments indicated by symbols given in the key. The numbers listed in the left-hand column are measured parametric values. The numbers in the right-hand column are the number of devices

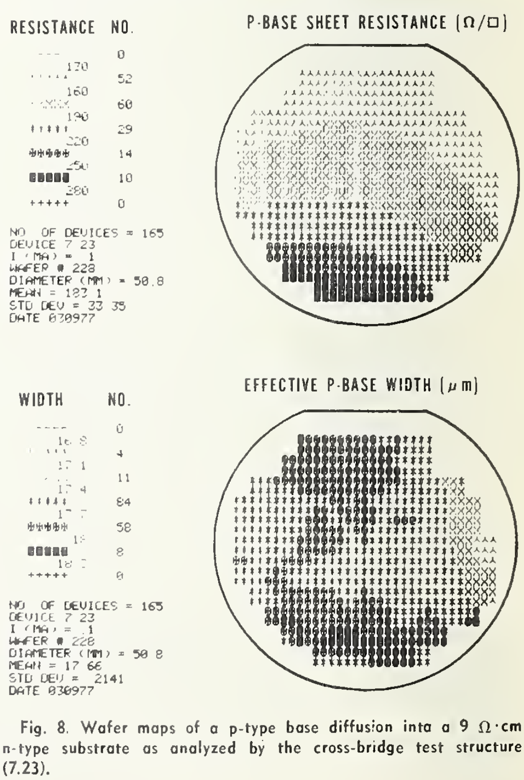

Fig. 8. Wafer maps of a p-type base diffusion into a 9 Ω·cm n-type substrate as analyzed by the cross-bridge test structure (7.23).

measured in each increment. Every other symbol shown in the wafer map represents a measured point; from these values the remaining symbols were obtained by interpolation. The sheet resistance shows a rather large top to bottom variation which is indicative of a diffusion problem; however, the effective line width shows a reasonably flat profile which is indicative of good etch control. Similar wafer maps have been reported elsewhere (6) for both the base and emitter sheet resistors using separate cross and bridge structures.

The use of the cross-bridge method in evaluating the width of very narrow diffused (or implanted) layers should be viewed with caution. This situation occurs when the incremental lateral diffusion width αX_j is comparable with the over-all width. In fact, the caution applies to any layer in which strong lateral resistivity gradients exist. In such cases the effective sheet resistance determined at the cross may not be the correct value for use in the computation of the effective width from Eq. [2]. The method described here has also been applied to the measurement of the line width of phosphorus emitter diffusions with a sheet resistance of about 1 $\Omega/\square$ (5, 6). In addition, the width of aluminum metallization with a sheet resistance of about 0.03 $\Omega/\square$ has been measured.

Conclusion

It was demonstrated that effective line width can be determined from electrical measurements on diffused bridge and van der Pauw sheet resistors and that these electrical measurements agree with those determined from optical photomicrographs of the sheet resistors. The method is sensitive to width changes of the order of ± 0.1 μm (± 4 μin.). A new cross-bridge sheet resistor was developed; wafer maps of the sheet resistance and line width illustrate the utility of this structure for process control.

The advantage of electrical line-width measurements is that they can be made quickly and at low cost using automatic data acquisition equipment with sufficient voltage resolution. Thus these measurements are important because of their potential use as process control and design vehicles in the manufacture of semiconductor devices.

Acknowledgment

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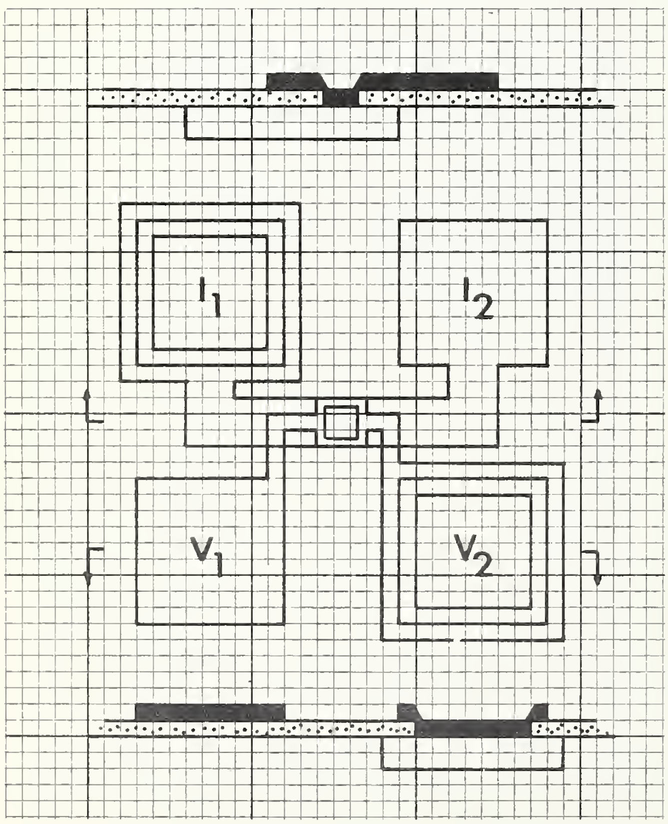
APPENDIX B

B-1. Metal-to-Base Contact Resistor, Structure 3.24

Metal-to-base contact resistor, structure 3.24, is a four-terminal resistor which consists of a base diffused into the collector and metal which touches the base at a square window 1.00 mil (25.4 μm) on a side; see figure 1. The effective contact resistance for a unit area, R_c, as given by this structure is calculated from

$$R_c = AV/I \tag{1}$$

where the potential, V, is V_1-V_2 for a current, I, passed into I_1 and out of I_2 and A is the area of the contact. For a square contact window of 1.00 mil (25.4 μm) on a side, $A = 6.45 \times 10^{-6}$ cm^{-2}. This structure is intended to serve as a process control monitor. It is not intended to yield absolute values for the specific contact resistance, for the specific contact resistance determined by this structure is influenced by over-etch of the contact window and by current crowding effects since only a fraction of the contact carries a significant current [B-1]. Over-etch of a contact window occurs because the contact window is etched at the same time as the scribe lines. Etching the scribe lines requires removal of the collector oxide which is thicker than the base oxide.



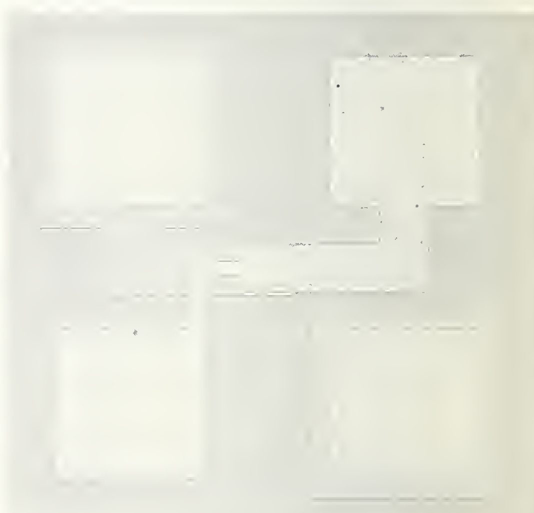


Figure 1. Photomicrograph of the metal-to-base contact resistor, structure 3.24.

Reference:

B-1. Kelley, F. R., Mattis, R. L., and Buehler, M. G., Metal-to-Base Contact Resistor Study, *Semiconductor Measurement Technology*, W. M. Bullis, Ed., NBS Special Publication 400-1 (March 1974), pp. 22-25.

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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.)*

Microelectronic test pattern NBS-15 is composed of several potentiometric, production-compatible electrical alignment resistor test structures, visual alignment indicator test structures, cross bridge sheet resistors, and contact resistor test structures. The pattern was originally designed as a study vehicle for the electrical alignment resistor, but it was also demonstrated that, when stepped over an entire wafer, the pattern is suitable for use in evaluating misalignment which may result from photomask generation, photomask exposure, or other fabrication processes. This report summarizes the test structures that are included in the pattern and contains explanation of how each of the structures is measured.

17. KEY WORDS *(six to twelve entries; alphabetical order; capitalize only the first letter of the first key word unless a proper name; separated by semicolons)*

Contact resistor; cross bridge sheet resistor; electrical alignment resistor; semiconductor; silicon; test pattern; test structures; visual alignment.

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