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DIRECT MEASUREMENT OF THE DEPLETION LAYER WIDTH VARIATION VS APPLIED BIAS FOR A PN JUNCTION

by

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ERL Technical Memorandum M-130

6 October 1965

ELECTRONICS RESEARCH LABORATORY

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The research reported here was supported in part by the Joint Services Electronics Program (Air Force Office of Scientific Research, Army Research Office, Office of Naval Research) under Grant AF-AFOSR-139-64 and by the U. S. Department of Air Force under Contract AF 33(615)-1045.

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Using the scanning electron microscope, the width of the depletion region of a reverse-biased silicon N^+P junction was measured as a function of the applied voltage. It was observed that as the reverse bias across the junction is increased, dynamical broadening of the depletion layer occurs in both the voltage-contrast and the electron-beam-induced current (EBIC) modes of operation.[1] In the voltage-contrast mode of operation, a primary electron beam approximately 0.1 micron in diameter is scanned in a raster pattern over the sample, and secondary electrons produced by this beam are collected. The resulting video signal modulates the intensity of a synchronously scanned cathode-ray tube (CRT). The relative intensity of different areas on the CRT display have been shown to be a measure of the potential on the sample surface corresponding to those areas. In the EBIC mode of operation, the video signal is proportional to the currents generated in the device by the electron beam; if the primary beam's energy V_0 is lost in a depletion region, these currents may be approximately $V_0/5$ times greater than the primary beam current.[2] In the experiments reported here, the beam energy V_0 was 18 kv, the beam current I_0 was approximately 0.5 nanoamp, and the maximum EBIC was approximately 2 μamp.

The width of a depletion region of a one-dimensional abrupt planar N^+P junction is related to the applied voltage by the following well-known equation,

$$w = \left[\frac{2\epsilon}{qN_a} \ (V_a + V_d)\right]^{1/2} , \qquad (1)$$

where w is the depletion region width, ϵ is the dielectric constant of the semiconductor, N_a is the acceptor concentration on the high-resistivity side of the junction, V_a is the applied voltage, V_d is the diffusion voltage, and q is the electronic charge. If the junction position is known, and if the depletion region boundaries can be detected with an accuracy of one micron or more, depletion-region widening should be observable for acceptor atom concentrations in silicon of approximately 10^{15} atoms/cm^3, or less.

A lapped metal-oxide-semiconductor field-effect transistor (MOSFET), shown schematically in Fig. 1, was used in the measurements described below. A phosphorus diffusion into a high-resistivity (350 ohm-cm) P-type silicon substrate was used to form the passivated N^+P junction. The specimen was then lapped at an angle of approximately 25^o with the device surface in order to expose the junction region. A thin layer of aluminum was evaporated onto the N^+ diffused region, and a gold lead was bonded to this aluminum. The bottom of the device was gold-bonded to a transistor header, forming the electrical contact to the high-resistivity P-type material.

This device was mounted in the scanning electron microscope such that the normal to the lapped surface subtended an angle of about 20^o to the incident electron beam. This tilting improves the collection of secondary electrons, which were used to produce the micrographs shown in Fig. 2. In each micrograph, the upper portion is the usual device surface, and the lower portion is the angle-lapped surface. The dark central band is the width of the N^+ diffusion region plus the depletion region. The reverse bias of micrographs (a), (b), and (c) in Fig. 2 is 4.5, 9.0, and 18v, respectively. The solid line on these micrographs marks the edge of the lapped region, and the dashed line marks the edge of the depletion region. The depletion region width is the width of the dark region minus the diffusion depth of approximately 1 micron. Eleven micrographs similar to those shown in Fig. 2 were obtained for applied voltages ranging from 1.5 to 24 v. The width of the dark region was scaled from each micrograph, and after subtracting the 1 micron diffusion depth, the depletion region width was plotted vs the square-root of the applied voltage. The resulting points are shown on Fig. 3. In this experiment, the estimated error in determining the edge of the depletion region from the micrographs was estimated to be ± 1 micron, as indicated by the vertical line on the experimental points. The slope of the straight line drawn through the points indicates an acceptor atom density $N_a = 5 \times 10^{13}$ atoms/cm^3, while the resistivity measured with a four-point probe of 350 ohm-cm indicates a slightly lower value, $N_a = 4 \times 10^{13}$ atoms/cm^3. The dashed reference lines, in (b) and (c) in Fig. 3, correspond to acceptor atom densities of 10^{13} and 10^{14} atoms/cm^3, respectively. This degree of correspondence between the four-point probe measurement, and the novel method of measurement reported here indicates that the edge of the darkened region on the scanning electron micrograph does correspond to the edge of the depletion region. Measurements on the same device using the EBIC signal yielded the same doping within our experimental error.

The method described above may prove especially useful for evaluating effective dopant concentrations in certain regions of closely-spaced semiconductor devices, such as arrays of metal-oxide-semiconductor field-effect transistors, in which space limitations preclude the use of four-point probes or other normally used techniques. However, the above method has decided limitations. First, its accuracy decreases as doping of the semiconductor increases. Second, on certain samples, particularly those with very thin layers of passivating oxide, electron-beam bombardment of this sort has been observed both in our laboratory and elsewhere[3] to induce changes in the device characteristics and/or the observed surface potential. Third, Eq. (1) refers to a one-dimensional geometry, which is a good approximation in the interior of a planar junction device, but not at a beveled surface. Potential distributions on the surface of devices geometrically related to those considered here have been published by Davies and Gentry.[4] Their computed results should correlate with measurements made by this method; such measurements are planned.

In conclusion, we have demonstrated that variations in the applied depletion-layer width produced by variations in the applied reverse bias across N-P junctions can be observed and measured in the scanning electron microscope. The doping of high-resistivity material determined from such measurements agrees qualitatively with that determined from four-point probe measurements.

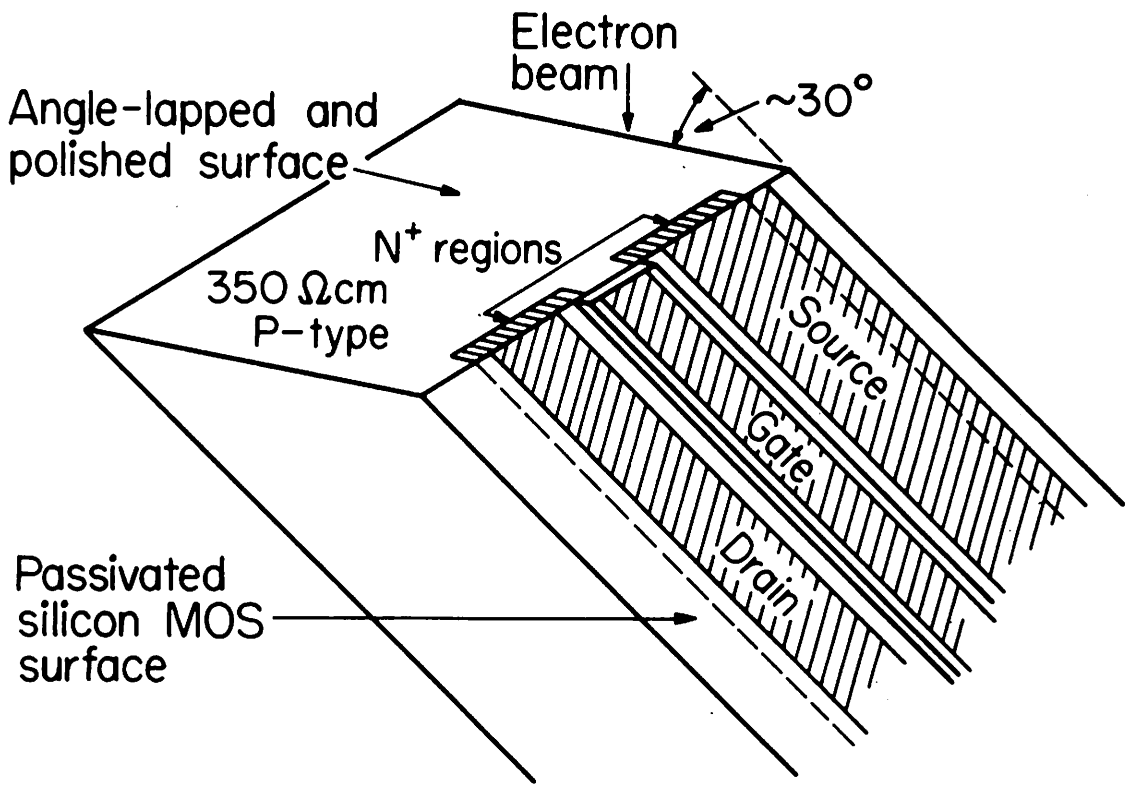

Fig. 1. Schematic diagram of angle-lapped, metal-oxide-semiconductor, field-effect transistor (MOSFET).

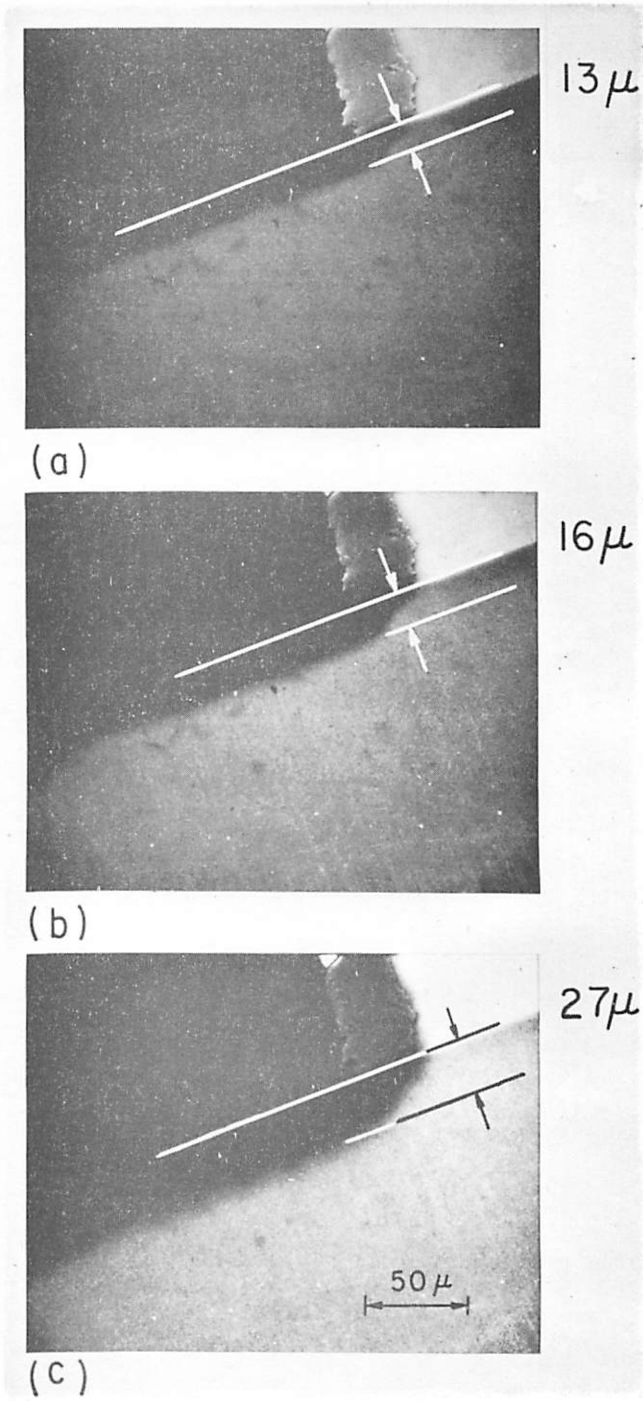

Fig. 2. Scanning electron micrographs of MOSFET.
(a) reverse-bias = 4.5 v
(b) reverse-bias = 9.0 v
(c) reverse-bias = 18.0 v

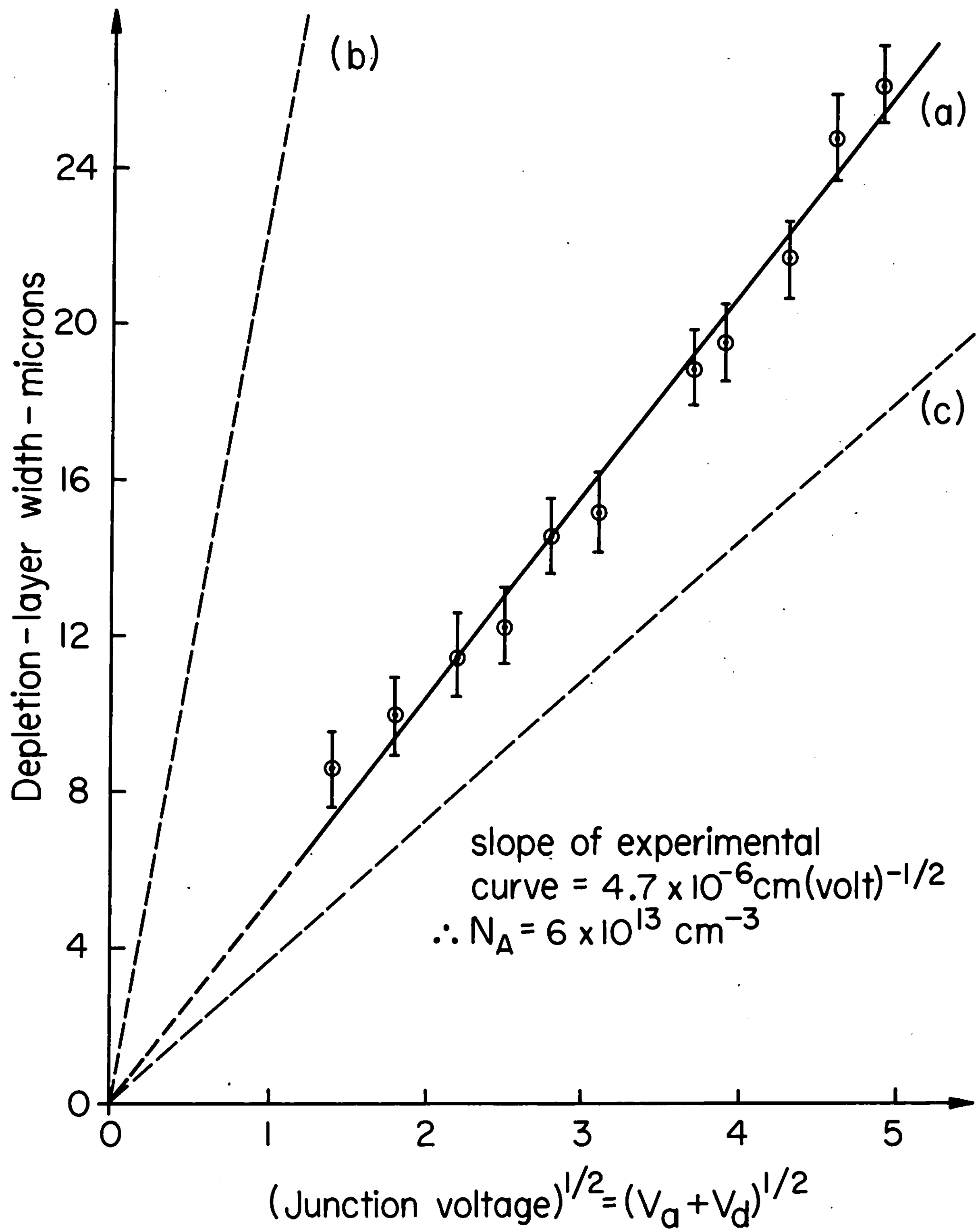

Fig. 3. Depletion-layer width plotted vs (junction voltage)$^{1/2}$.

REFERENCES

1. T. E. Everhart, O. C. Wells, and R. K. Matta, "Evaluation of Passivated Integrated Circuits using the Scanning Electron Microscope," J. Electrochemical Society, 111, 929-936, Aug. 1964.

2. T. E. Everhart, O. C. Wells, and R. K. Matta, "A Novel Method of Semiconductor Device Measurements," Proc. IEEE, 52, 1642-1647, December, 1964.

3. D. Green, J. E. Sandor, T. W. O'Keeffe, and R. K. Matta, "Reversible Changes in Transistor Characteristics Caused by Scanning Electron Microscope Examination," Appl. Physics Letters, 6, 3-4 (1965).

4. R. L. Davies and F. E. Gentry, "Control of Electric Field at the Surface of P-N Junctions," IEEE PTG-ED-11, 313-323, July, 1964.