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Electrode Control of SiO_2-Passivated Planar Junctions

Abstract: Electric fields have been applied to the surface over a planar silicon junction by means of a metallic control-ring electrode on the oxide surface. Capacitance measurements have indicated that a large, positive, immobile charge is present at or near the interface between the silicon dioxide and the silicon. An improvement in breakdown voltage occurs when the control ring is biased negatively, producing a field that opposes the field of the immobile charge. Positive control-ring voltages are shown to produce very large junction leakage currents. The leakage current is shown to be sensitive to a high-temperature reverse bias treatment and a model for this effect is suggested. Transistors with base contracts that extend over the oxide-protected collector junction are shown to have higher breakdown voltages than do those that lack the base electrode extension. This effect is consistent with the improvement in breakdown voltage found in control-ring diode measurements.

Introduction

Two characteristics of planar silicon junctions that are observed rather consistently cause concern to device design engineers:

(1) High-voltage planar junctions have breakdown voltages considerably lower than those predicted[1] from impurity density profiles.

(2) Junction leakage currents have been observed to increase by orders of magnitude under the combined influence of reverse bias and high operating temperature.

Since both effects (1) and (2) appear to be related to the surface condition of the silicon, a study was made to determine quantitatively what surface conditions would produce them. For this purpose, planar junctions were made with a control-ring electrode above the junction and insulated from it by the SiO_2 film (Fig. 1). In this experimental control-ring diode, the surface potential can be varied at will by adjusting the voltage applied to the ring. Capacitance measurements to be given here will establish the relationship between the voltage of the control ring and the surface potential of the high-resistivity side of the junction. Breakdown voltage and junction leakage current are then empirically related to the surface potential by an analysis of the effects of control-ring voltage.

A study has been made by Sah[2] on the emitter junction of a transistor to determine the transistor gain as a function of surface potential. The work described here differs from Sah's work in that the junction under study is reverse biased, resulting in large internal fields, rather than forward biased. Also, use is made of the surface capacitance measurement to determine surface conditions, whereas Sah's device was not suitable for such a measurement.

The results of the work described here show the beneficial action of a metallic contact that is connected to the diffused *p*-region and extends over the oxide-protected junction edge. Similar results on such "extended contacts" have been reported by Clark and Mack[3].

This paper presents the measurements on a control-ring diode, showing the quantitative relation between

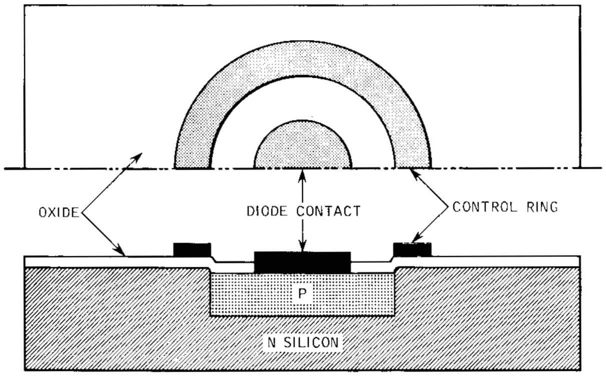
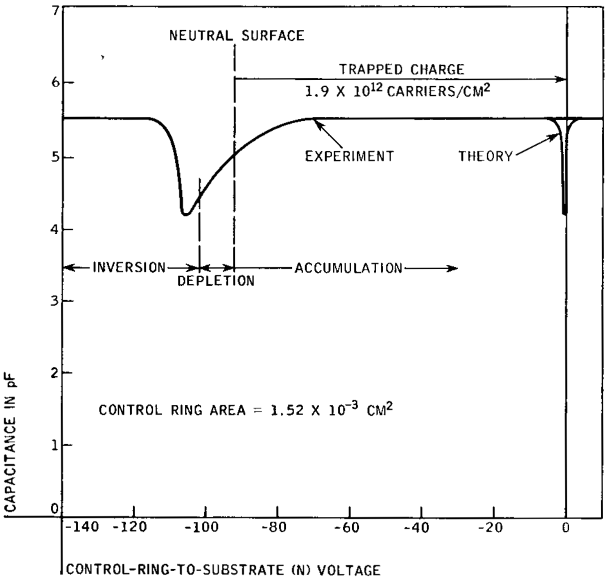


Figure 1 **Experimental control ring diode.**

Figure 2 **Control ring capacitance vs voltage.**



surface condition, junction leakage current, and breakdown voltage. In addition, the characteristics of transistors made with and without extended base contacts will be compared.

Control ring diode

Planar silicon diodes were made by diffusing boron into a 5.9 ohm-cm, *n*-type silicon epitaxial layer. The diffusion was a two-step process; first B_2O_3 was deposited at 900°C. Then the boron on the surface was diffused into the silicon at 1200°C. The impurity concentration at the surface was 2×10^{18} cm^{-3} and junction depth after diffusion was ~0.16 mil. An aluminum control ring was evaporated on the oxide and trimmed by subtractive etching. It overlapped the junction by ~4μ (Fig. 1) with most of its area over the *n*-side. Oxide thickness was estimated to be 9750 Å from a calculation involving the measured control-ring capacitance. Several wafers of these control ring diodes were made with similar characteristics. The measurements described here were typical of a large number of the units.

Assuming an abrupt junction (impurity gradient is greater than 10^{20} atoms/cm^4 at the junction), a breakdown voltage of greater than 300 volts would be expected.[1] Measured values, however, were generally less than 200 volts with the control ring unconnected.

Capacitance measurements

Figure 2 shows a comparison of the typical capacitance between control ring and substrate as measured and as predicted from theory[4] (immobile charge in surface states or space charge in the insulator being neglected in the theoretical calculation). A large, positive immobile charge of 1.9×10^{12} carriers/cm^2 is indicated by the horizontal difference between the two curves. A layer of immobile space charge in the oxide will extend a field normal to the surface and produce the same effect as a d-c voltage on the external electrode, resulting in a horizontal translation of the capacitance curve from its theoretical position. The effect of surface states is to widen the capacitance transition. Figure 2 shows that the width of the capacitance transition is greater than the theory indicates. This suggests the presence of surface states. Immobile charge densities of the magnitude observed are often present on thermally oxidized silicon surfaces. Since there is no way to determine experimentally the immobile charge density where the control ring overlaps the *p*-region, we have assumed it to be the same as that over the *n*-region. An immobile charge of 1.9×10^{12} cm^{-2} is sufficient to bring the Fermi level at the surface to the intrinsic level (onset of inversion) in material uniformly doped to a level of 5×10^{17} cm^{-3}. The diffusion process leaves an impurity density gradient which starts at 2×10^{18} cm^{-3} at the source (silicon surface) and decreases according to a Gaussian law at increasing distance from the diffusion source. Therefore, the *p*-surface is assumed to be inverted at zero control ring voltage in a region between the junction and a point where the impurity concentration is 5×10^{17} cm^{-3}. For this junction, the width of the *p*-side inversion region at zero control-ring bias under the preceding assumptions is 2.3 microns.

Figure 3 shows the capacitance between control ring and substrate for various junction reverse-bias voltages. The magnitude of the voltage on the control ring necessary to invert the surface of the *n*-side becomes very large when a reverse bias is applied. This effect, which was predicted by Young and Thomas[5] is due to the field of the junction that extends under the control ring and sweeps away minority carriers as they are generated at the surface. Thus, from the capacitance curves of Figs. 2 and 3, one

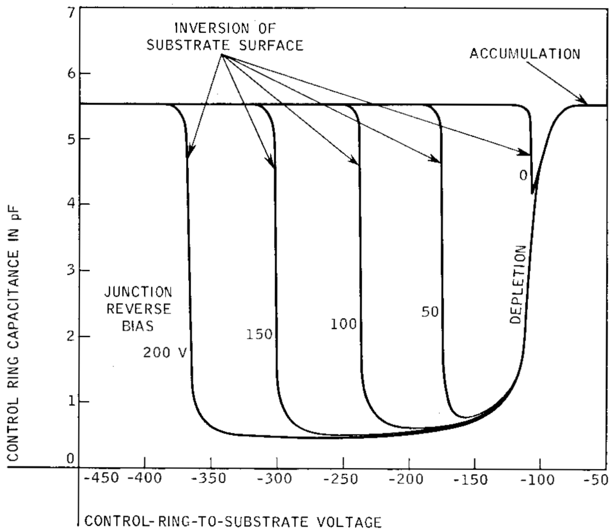


Figure 3 **Control ring capacitance vs voltage for different various values of junction bias.**

can state the condition of the *n*-side surface for any applied junction reverse bias and any control ring to substrate voltage. The surface then can be roughly described as being accumulated, depleted, or inverted. With certain assumptions, one can also make similar statements about the *p*-side surface.

Breakdown voltage

Figure 4 shows the avalanche breakdown voltage as a function of the voltage between control ring and *p*-region. For a device without a control ring, one would expect to find a breakdown voltage equal to a value at some positive control-ring voltage in Fig. 4. This is expected because the oxide surface must assume a potential between zero and some positive voltage less than or equal to the applied junction voltage.[6] The control ring offers other possibilities, and, in fact, a control ring voltage of -60V (to the *p*-side) yields a maximum breakdown of 265V. This control-ring voltage is not sufficient to neutralize all of the assumed immobile positive charge on the *p*-side. At the maximum breakdown voltage, the voltage between control ring and *n*-side is:

$$V_{\substack{\text{control}\\ \text{ring}/N}} = V_{\substack{\text{control}\\ \text{ring}/P}} + V_{P/N} = -60-265 = -325 \text{ V}.$$

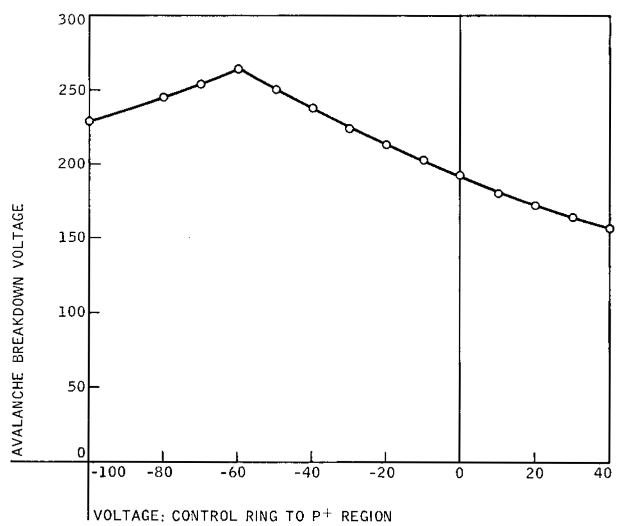
From Fig. 3, this value falls in a low-capacitance region for a junction voltage magnitude greater than about 175 V, indicating that the *n*-side surface is depleted but not inverted. As used here and throughout the text, the term "inverted" refers to a significant density of mobile carriers at the surface of a type opposite to those in the bulk. A low value of control-ring capacitance indicates few mobile carriers of either type at the surface. At present it is not completely understood why an optimum control-ring voltage exists beyond which breakdown decreases. It seems clear that the immobile charge in the oxide or at the oxide-silicon interface intensifies the field in the depletion layer of the junction where it intercepts the surface, leading to a value lower than bulk avalanche breakdown voltage. This occurs because the externally applied field adds to the field of the depletion layer at the surface. One would expect, therefore, that the application of a field in opposition to that of the immobile charge would increase the breakdown voltage, until the surface breakdown is greater than the bulk value. At this point, further increase in control-ring voltage should have no effect. Figure 4 indicates the expected increase for negative control-ring voltage, but does not show a saturation, indicating that the breakdown in this device is always surface limited.

Junction leakage

The reverse current of the control-ring diode was found to be strongly dependent on positive control-ring voltage. A family of reverse current-voltage curves is shown in Fig. 5. The exponential rise and saturation region strongly resembles the curves reported by Nathanson,[7] where the mechanism was ascribed to tunnelling across the junction at the surface. Figure 2 indicates strong accumulation in the *n*-region for positive control-ring voltages, and by implication, inversion of the *p*-side.

A control-ring diode was put under test for one hour at 200°C and 20 V reverse bias, with the control ring connected to the *n*-side. The diode was cooled without remov-

Figure 4 **Junction avalanche breakdown voltage control by ring bias.**



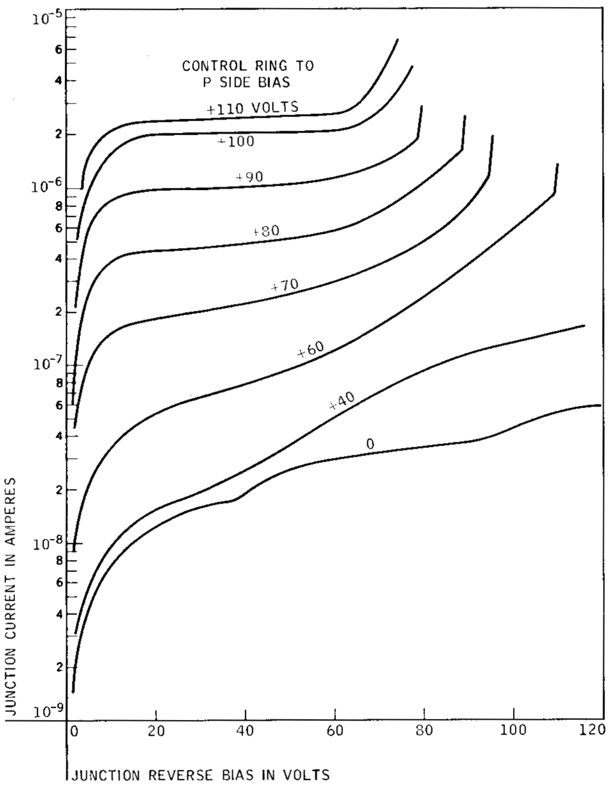


Figure 5 **Current-voltage characteristics for positive values of control ring bias.**

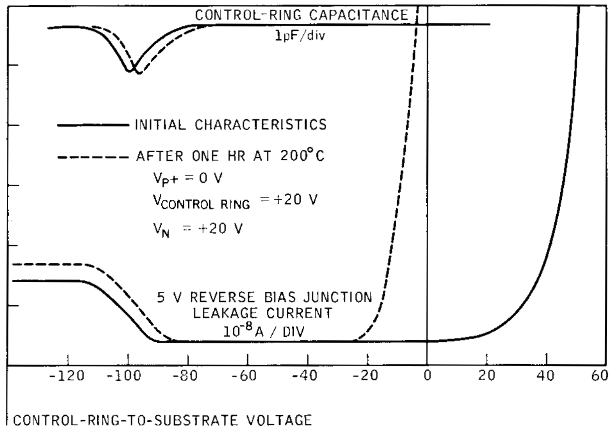


Figure 6 **Effect of junction bias-temperature treatment on control ring diode leakage.**

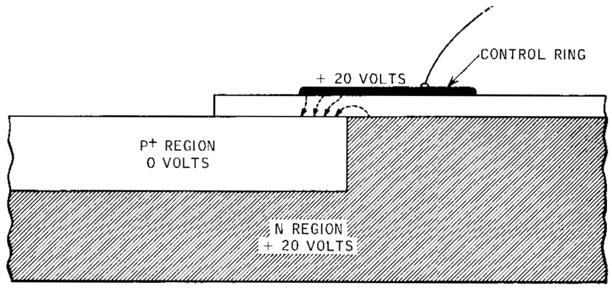


Figure 7 **Field direction during temperature—reverse bias stress.**

ing the bias. Junction leakage current at 5 V reverse bias was measured as a function of control-ring voltage before and after treatment (Fig. 6). The capacitance curves in Fig. 6 show that the *n*-region surface has been only slightly changed and that when the *n*-region becomes inverted (control-ring voltage <-100 V), a leakage current increase is observed. This effect exists both before and after high-temperature bias treatment. The magnitude of this increase is in rough agreement with the effective increase of junction area (4×) upon the formation of an inversion region under the control-ring electrode. At zero and positive gate voltages, however, the leakage current has increased by large amounts because of the temperature-bias stress. (A phosphosilicate layer on the oxide inhibits this effect).[8] This change can be explained only by a local change of surface potential. Two possibilities exist: a local *n*-type surface shift on either the *p*-side or the *n*-side. Previous experience[8] has shown that fields directed out of the surface during heating will cause either a shift in the *p*-direction, or no shift at all, and fields directed into the surface during heating cause a shift of the surface potential in the *n*-direction. Figure 7 shows the direction of the field during the combined temperature - reverse bias treatment. From this, we conclude that the *p*-region has been shifted in an *n* direction, because the *n*-region was stressed in a direction opposite to that which would explain the observed effect.

The large increase of leakage current has been observed on other diffused junction control-ring diodes, both *p* on *n* and *n* on *p*.[9] In all cases, the conditions under which the current is observed are that the high-resistivity side is in accumulation at the surface, and the low-resistivity side is being driven into inversion near the junction. It is possible that when the diffused surface inverts, field emission takes place there. It is also possible that saturation of the current in Fig. 5 results from a "pinch-off" of the narrow inversion channel which must conduct the excess leakage current. Calculations of typical field strength and space charge layer width for inverted material of 10^{18} cm^{-3} doping level gives values such as 5×10^5 V/cm and 400 Å, respectively.[10] Chynoweth and McKay[11] have found that field emission can occur in silicon junctions of this width at zero bias, so that it does not seem unreasonable to expect such behavior here.

Extended base contact

It is clear from the foregoing that a control ring that is connected to the diffused region will tend to create the conditions necessary for high breakdown and low leakage current. An experiment was conducted to determine the improvement in breakdown voltage that could be obtained in the collector junction of a transistor whose base contact extends over the oxide-protected collector junction as in Fig. 8. These transistors are referred to as "extended base contact" transistors.

Planar transistors with 500°C sintered aluminum contacts and abrupt collector junctions were made in 0.9 ohm-cm *n*-type material. The contact geometry was alternated by row between extended and non-extended base contacts. The extended base contact units have 89 V breakdowns, which is 30 V higher than the non-extended contact units. This compares favorably with the theoretic abrupt breakdown of 90 V for 0.9 ohm-cm *n*-type material.[1] The electrical characteristics for ten units (five extended and five non-extended) are shown in Table 1. The table shows also that the extended base contact has little effect on properties other than breakdown voltage.

The same experiment was repeated using epitaxial material with resistivities ranging from 0.6 to 2.0 ohm-cm. The difference in breakdown voltage between the extended and non-extended contact units increased as the resistivity increased; however, no detectable difference of breakdown voltage was observed in 0.6 ohm-cm material. The experimental data are plotted in Fig. 9.

This unexpected result might be explained by a weakening of the depletion region field at the surface because of fringing effects. We would expect the surface junction field to be lower than the bulk field were it not for the presence of excess immobile charge. The depletion width narrows as the resistivity decreases, causing the fringing field strength to rise until it can neutralize the field of the immobile charge. It therefore appears that the magnitude of the fringing field in 0.6 ohm-cm material for our sample is sufficient to insure that the breakdown observed is the bulk breakdown.

Summary

Measurements have been made of control-ring capacitance, junction breakdown voltage, and junction leakage

Figure 8 **Extended base contact transistor.**

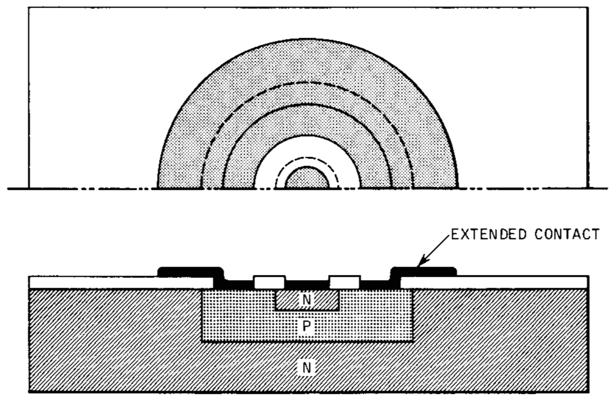


Table 1 **Characteristics of extended base contact (EBC) and non-extended base contact (NEBC) transistors.**

Unit No.	BV_{EBO} *at* 10 μA	BV_{CBO} *at* 10 μA	BV_{CEO} *at* 5 mA	FV_{EBO} *at* 10 mA	I_{EBO} (nA) *at* 5 V	I_{CBO} (nA) *at* 40 V	β *at* I_C = 10 mA	β *at* I_C = 100 mA
EBC								
001	9.1	86.0	56.0	.72	5	8	23.0	52.0
002	8.0	89.0	54.0	.70	2	2	19.0	35.5
003	9.2	89.0	56.0	.71	21	19	17.0	35.5
004	8.5	89.0	52.0	.71	11	16	23.0	35.5
005	8.4	89.0	52.0	.71	2	4	26.0	50.0
NEBC								
006	8.0	50.0	38.0	.83	30	51	23.0	40.0
007	8.9	46.0	51.0	.71	12	35	21.0	52.0
008	8.8	60.0	54.0	.74	264	>1K	23.0	66.0
009	8.9	62.0	50.0	.72	27	12	34.0	66.0
010	8.8	55.0	53.0	.72	12	57	26.0	66.0

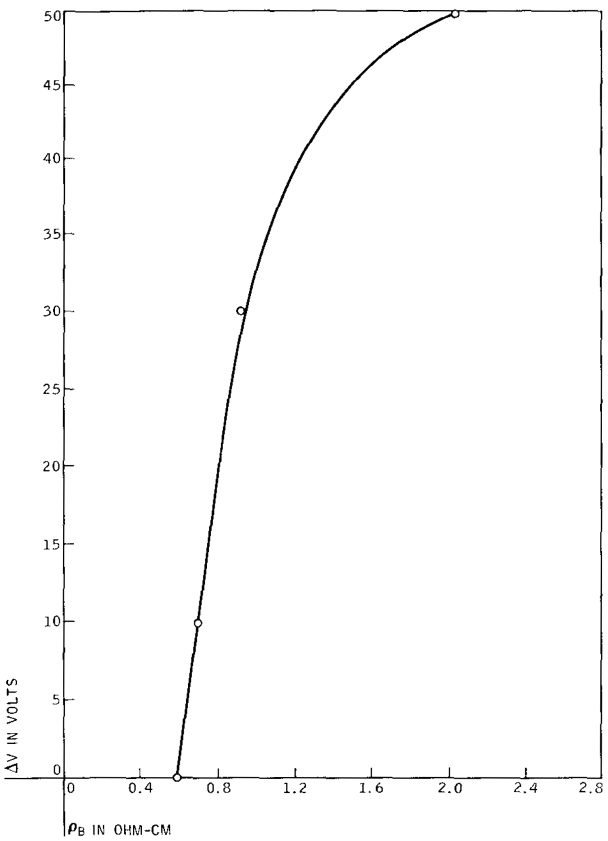


Figure 9 **Difference (ΔV) in breakdown voltage between transistors with extended and non-extended base contacts vs bulk resistivity (ρ_B).**

current as functions of the control-ring dc potential. The principal results of these measurements are:

1. There is an optimum value of control-ring voltage, at which breakdown voltage is a maximum.

2. At control-ring voltages such that the diffused *p*-region is becoming inverted near the junction, reverse leakage current rises exponentially with control-ring voltage in a manner similar to that described by Nathanson et al.[7] Rough calculations show that field emission would be a possible mechanism for this current.

3. Junction leakage current at small reverse bias increases when the *n*-surface is inverted, by an amount roughly proportional to the junction area increase.

4. Heating during reverse bias alters the functional dependence of junction leakage current on control-ring voltage. The effect is consistent with inversion of the *p*-region surface next to the junction, due to buildup of immobile positive charge in the oxide during heating and bias.

A technique for utilizing the ohmic contact electrode to control the surface over the junction has been shown to be effective in approaching the bulk breakdown values.

It should be noted that an additional benefit of placing a metal electrode over the insulated junction (as with the extended base contact) is that drifts of the junction characteristics caused by slow changes of the potential at the outside surface of the insulator are completely prevented.[12] Potential changes of this type associated with surface leakage have been discussed by several authors.[6,13–15]

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References and footnotes

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