

PHYSICAL REVIEW LETTERS

VOLUME 11

1 DECEMBER 1963

NUMBER 11

CHARGES ON OXIDIZED SILICON SURFACES*

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(Received 16 September 1963)

The presence of mobile charges on semiconductor surfaces has been postulated by several authors in order to account for certain surface phenomena. For example, Brown¹ in his early measurements of inversion-layer channels offered this hypothesis to explain channel "conditioning," i. e., bias- and ambient-dependent conductance variations. Statz and co-workers² postulated motion of charges at the surface which were thought to change the conductivity of an underlying channel.

Atalla and co-workers³ discussed a model in which an electric field separates ions of opposite charges on the oxidized surface of a silicon p - n junction when reverse bias is applied across the junction to produce an electric field with a large tangential component parallel to the surface. This "Atalla model" of ionic separation was used to explain the spreading of channels as observed by photocurrents and other electrical characteristics. The theory includes the idea that the ionic charge produces electric fields through the oxide that may approach the breakdown strength.

The present work was undertaken after reaching the conclusion, not discussed by Atalla, Bray, and Lindner,³ that the high electric fields through the oxide should produce "work functions" or contact differences in potential comparable to the applied reverse bias across the junction. A direct measurement of these potentials would confirm the surface-charge hypothesis and the Atalla model, as well as furnish a new tool for studying surface effects.

In this Letter we report such direct measurements of surface potentials, utilizing the Kelvin method.

The specimens consist of diffused p - n junction diodes, covered with thermally grown oxides between 300 and 1000Å thick. Substrate resistivity is 1 Ω-cm, p . These specimens are scanned with a circular gold plate of 300-μ diameter, held parallel to the surface, vibrating perpendicular to its normal at 390 cps close to the surface. The ac signal is nulled with a bucking voltage applied between the silicon and the plate which then directly gives the contact potential difference. Two different ambients are employed. The "dry" condition is determined by laboratory air at room temperature and 35% relative humidity, while the "wet" condition is given by exposure to air with close to 100% humidity.

Figure 1 shows a set of typical results. Equilibrium is indicated by curve *a*, showing a constant small contact potential across the surface. Curve *b* is the distribution after applying a reverse bias of +20 V to the n side: there is a sharp potential drop on the oxide directly above the p - n junction. However, this distribution drifts towards one with a more gradual potential drop. This drift is accelerated in the "wet" condition (curve *c*). After reinstalling the "dry" condition, the bias is removed, and curve *d* is measured. This distribution decays towards curve *a* with a time constant of several minutes when "dry," and fractions of seconds when "wet."

We interpret these results as follows. The ap-

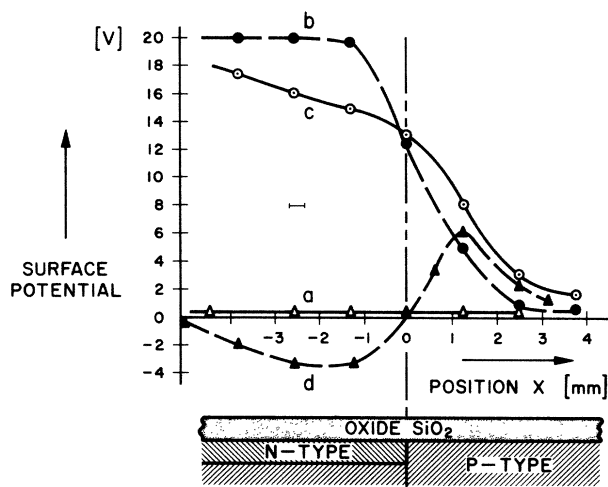


FIG. 1. Surface potential vs gold of a silicon p - n junction covered with approximately 1000 \AA of oxide, plotted versus distance x from the junction. Curve a , equilibrium; curve b , reverse bias of $+20 \text{ V}$ applied to n region ($x < 0$), p region grounded; curve c , after exposure to "wet" ambient with bias applied; curve d , "dry" ambient restored and bias removed; evidence for residual charges on oxide. Bar indicates size of vibrating probe.

plied field causes a motion and redistribution of charges on the oxide surface and possibly also within the oxide. The distribution is such as to reduce the external field, i. e., positive charges accumulate on the p side, which is biased negative with respect to the n side, and vice versa. This charge arrangement is aided by water vapor, which probably increases concentration and mo-

bility of the ions or dipoles. It is remarkable that after voltage removal, the remaining charge corresponds to as much as 50% of the previous bias.

The potential distributions, as shown in curves b to d , and the associated time constants of the drifts depend sensitively upon surface treatment and ambient. For example, a soaking with methanol yielded drift time constants of a few seconds for the positive charges, but of several minutes for the negative charges. Such details are currently being investigated with the hope to identify nature and transport mechanism of the charged entities.

These surface charges may be interpreted as a form of mobile slow states. They, in turn, exert influences upon the underlying semiconductor. We found correlations between surface potential and channel conductance as well as with breakdown voltage. These results are similar to those of Atalla, Bray, and Lindner³ and in agreement with models⁴ ascribing changes in junction behavior to surface charges.

The authors thank Dr. R. Gereth for valuable suggestions regarding the apparatus.

*Research supported by Rome Air Development Center, U. S. Air Force.

¹W. L. Brown, Phys. Rev. **91**, 518 (1953).

²H. Statz and G. A. deMars, Phys. Rev. **111**, 169 (1958).

³M. M. Atalla, A. R. Bray, and R. Lindner, Suppl. Proc. Inst. Elec. Engrs. (London) Pt. B **106**, 1130 (1959).

⁴C. G. B. Garrett and W. H. Brattain, J. Appl. Phys. **27**, 299 (1956).

FERROMAGNETIC RELAXATION IN EUROPIUM IRON GARNET

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(Received 29 August 1963; revised manuscript received 4 November 1963)

In recent years two theories have been proposed to explain ferromagnetic relaxation in rare earth iron garnets (REIG). The earlier theory, proposed by de Gennes *et al.*,^{1,2} is called the "fast" relaxation theory, because the assumption is made that $\tau_{RE} \ll \omega^{-1}$ over most of the temperature range, where ω is the operating frequency.

The other theory, originally proposed by Galt³ and Clogston⁴ and developed in some detail for YbIG by Teale and Tweedale⁵ and by Van Vleck and Orbach⁶ as well as more generally by Hartmann-Boutron,⁷ is called the "slow" relaxation theory because here τ_{RE} is assumed comparable to ω over the temperature range of interest.

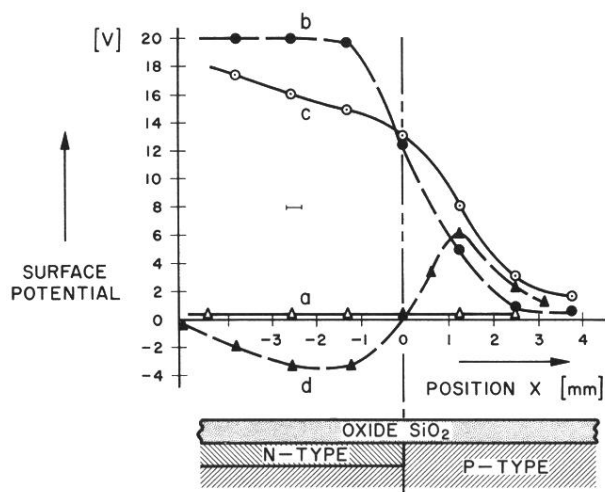


FIG. 1. Surface potential vs gold of a silicon $p-n$ junction covered with approximately 1000 \AA of oxide, plotted versus distance x from the junction. Curve a , equilibrium; curve b , reverse bias of $+20 \text{ V}$ applied to n region ($x < 0$), p region grounded; curve c , after exposure to "wet" ambient with bias applied; curve d , "dry" ambient restored and bias removed; evidence for residual charges on oxide. Bar indicates size of vibrating probe.