

BARRIER LOWERING AND FIELD PENETRATION AT METAL-DIELECTRIC INTERFACES

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Citation: [Applied Physics Letters](#) **9**, 53 (1966); doi: 10.1063/1.1754598

View online: <http://dx.doi.org/10.1063/1.1754598>

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whether the Brillouin frequency is pulled upwards or downwards to the nearest mode.

Attempts to observe a beat signal when the ruby amplifier is passive at the Brillouin frequency, but regenerative at the peak of the R_1 line shape, were generally not successful. Oscillation invariably occurred in both spectral regions and prevented the obtaining of the true Brillouin shift.

It is clear that if precise shifts are to be obtained, either the Brillouin backscattered light must be monitored directly along with the excitation (which presents a difficult optical alignment problem in the case of optical beats) or the ruby amplifier must be made passive. Whether passive amplification was maintained in the previous work is open to question.¹⁴

The author acknowledges the excellent technical assistance of K. L. Foster, and a useful conversation with D. Caddes and C. D. Wilkinson of the Stanford Microwave Laboratory.

¹C. H. Townes, *Advances in Quantum Electronics*, ed. by J. R. Singer (Columbia University Press, New York 1961), p. 3.

²E. Garmire and C. H. Townes, *Appl. Phys. Letters* **5**, 84 (1964).

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⁵D. I. Mash, V. V. Morozov, V. S. Starunov, E. V. Tiganov, and I. L. Fabelinskii, *JETP Letters* **2**, 246 (1965), transl., p. 157.

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⁸A. A. Chaban, *JETP Letters* **3**, 73 (1966), transl., p. 45.

⁹For a review of the subject see L. Mandel and E. Wolf, *Revs. Mod. Phys.* **37**, 231 (1965).

¹⁰Optical beats in the forward stimulated Brillouin scattering at 123 Mc have also been detected by D. A. Jennings and H. Takuma, *Appl. Phys. Letters* **5**, 241 (1964).

¹¹Replacing the chemical Q -spoiler by a rotating prism did not alter the beat frequency.

¹²On occasion a second, weaker beat appeared, removed from the first by plus or minus the mode spacing. It was not determined whether the second beat resulted from multimoding near ν_L or ν_B .

¹³D. Sette in *Acoustics I, Volume XI/1 Encyclopedia of Physics*, Ed., S. Flügge (Springer-Verlag, Berlin, 1961), p. 275.

¹⁴Passive amplification has apparently been observed in at least one case. Rank, et al., using high-pressure gases found the shift changed continuously with pressure and by amounts less than the mode spacing. D. H. Rank, T. A. Wiggins, R. V. Wick, D. P. Eastman, and A. H. Guenther, *J. Opt. Soc. Am.* **56**, 174 (1966).

BARRIER LOWERING AND FIELD PENETRATION AT METAL-DIELECTRIC INTERFACES

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(Received 2 May 1966; in final form 3 June 1966)

(Al-SiO₂; MOS structures; E)

We report here photoemission measurements on Si-SiO₂-Al structures in which the metal-SiO₂ barrier energy has been determined as a function of the electric field strength E in the dielectric. The expected barrier lowering is the sum of two terms: a) the Schottky term, proportional to $E^{1/2}$ and b) a term due to the penetration of the electric field into the metal electrode, proportional to E . The experimental results are in good agreement with the model, where the Schottky effect involves the optical value of the dielectric constant of the oxide and the Thomas-Fermi screening distance in the metal is 1 Å. To our knowledge this represents the first unambiguous quantitative determination of

either effect in a polar dielectric, although the Schottky effect alone has been observed in silicon.¹

Silicon used in these studies was 0.0005/Ω-cm n -type in the form of (111) oriented circular slices about 20 mm in diam and lapped both sides to 250 μ. The silicon slices were cleaned in both organic and inorganic solvents and chemically polished in a 4:10 HF:HNO₃ solution to 150-μ thickness. Following the polish procedure they were quenched in concentrated HNO₃, rinsed in deionized water, and immediately oxidized in dry oxygen at 1200°C for 6 min. The oxide from the back of the samples was removed with hydrofluoric acid using photoresist techniques. Then, before metallization, 25 Å of the top oxide surface was removed with a 10:1 H₂O:HF solution. Aluminum dots of 0.030-in.

*Supported in part by the Office of Naval Research.

diam were then evaporated on the surface to a thickness of approximately 150 Å. The final oxide thickness was 550 Å as determined by low frequency capacitance measurements.

Photocurrents in the MOS devices were measured with a vibrating reed electrometer. The light source was a xenon short arc lamp and a quartz prism monochrometer. Intensity calibration was done with a Reeder thermocouple. Although the sample response increased at shorter wavelengths, the monochrometer dispersion and lamp characteristic caused a rapid decrease in light intensity, yielding an overall response which increased only slowly at shorter wavelengths. This fact virtually eliminated any problems due to scattered light. Maximum photocurrents were of the order of 10^{-11} A, while the dark current was less than 10^{-15} A.

The dependence of the photocurrent on photon energy was observed to follow a cubic law above threshold, very similar to that observed in vacuum photoemission.² This relationship is demonstrated in Fig. 1, where the cube root of the photocurrent is plotted vs photon energy. These data were taken with negative bias on the Al and correspond to electron emission from the metal. The intercepts on the $h\nu$ axis correspond to the Al-SiO₂ barrier energy at any particular value of applied bias. It

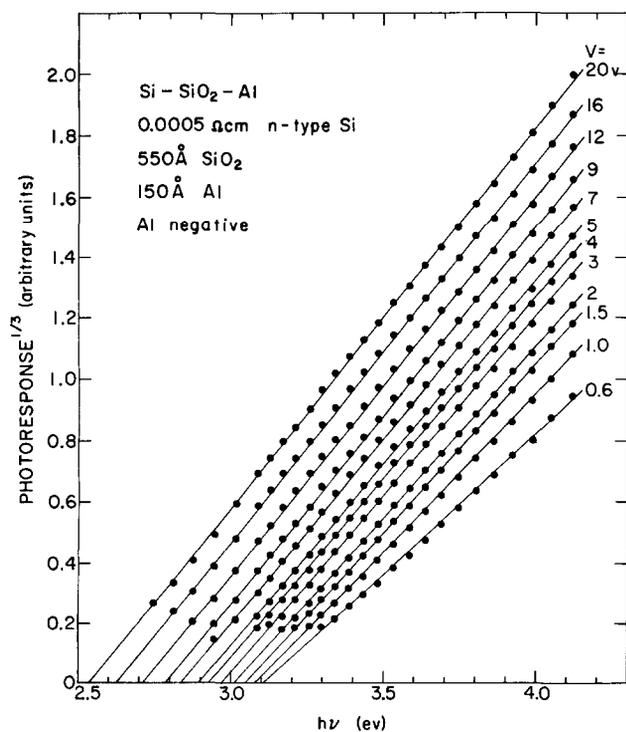


Fig. 1. Cube root of photocurrent (normalized to incident photon flux) as a function of photon energy for various negative voltages applied to aluminum electrode.

is clear that the barrier energy is lowered with approximately a square root dependence upon applied bias. In order to determine the exact form of this dependence, however, one needs to consider the voltage across the oxide which differs from the applied voltage by the difference between the metal-SiO₂ and Si-SiO₂ barrier energies.

Similar data taken with negative bias on the Si indicate a zero field Si-SiO₂ barrier energy³ between 4.35 and 4.4 eV, giving a built-in contact potential of approximately 0.1 V (Al positive with respect to Si). Band bending in the silicon will be negligible because of the heavy doping. Using this information the barrier energy can be plotted as a function of electric field in the oxide, as shown in Fig. 2. The result should be of the form⁴

$$\phi = \phi_0 - \left(\frac{qE}{4\pi\epsilon_0 K_H} \right)^{1/2} - K_L \lambda E \quad (1)$$

where ϕ_0 is the zero field Al-SiO₂ barrier energy; $K_H = 2.1$ and $K_L = 3.8$ are the high and low frequency dielectric constants of SiO₂ respectively; λ is the Thomas-Fermi screening distance in the metal,⁵

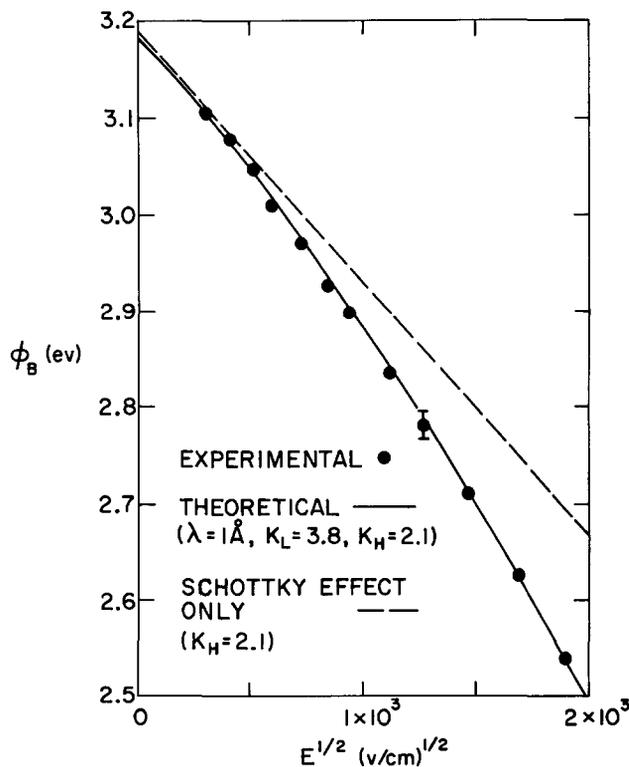


Fig. 2. Al-SiO₂ barrier energy as a function of the square root of the electric field in the SiO₂ as determined from intercepts of Fig. 1. Theoretical curve calculated from Eq. (1) using indicated values of dielectric constants and Thomas-Fermi shielding distance.

and the other constants have their usual significance. The dashed line in Fig. 2 is given by the $E^{1/2}$ term only. The solid curve is computed using the full expression assuming $\lambda = 1 \text{ \AA}$, and is seen to be in good agreement with the experimental results.

Several comments should be made concerning these results. First, the real nature of field penetration in the metal is not simply representable as an additive term as we have assumed, since it will also have an effect upon the image charges in the metal and hence on the image potential itself. Second, although the films used here are many times thicker than those of Braunstein et al.⁶ and Lewicki and Mead,⁷ they show none of the peculiar behavior of the latter. Third, the 1-\AA value of λ is somewhat larger than that calculated on the basis of any of the simple models.⁸ Any interfacial layer or lack of perfect uniformity in the metal-SiO₂ contact will produce a term linear in the field which would be undistinguishable from a larger λ in the metal. This may be responsible for the discrepancy in the present case. Finally, the effect of field pene-

tration would be greatly reduced by charge induced in surface states at the metal-SiO₂ interface. However barrier energies of different metals on similar SiO₂ structures were measured³ and found to vary approximately as the electronegativity of the metal, indicating the absence of any appreciable density of surface states.

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MODE COUPLING DUE TO BACKSCATTERING IN A He-Ne TRAVELING-WAVE RING LASER*

(mode coupling; frequency synchronization; T/E)

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In a previous paper,¹ Lamb's theory of an optical maser² was applied to a traveling wave system. The theory does not predict the experimentally observed frequency synchronization (lock-in)³ of the oppositely directed traveling waves (ODTW) in He-Ne type ring lasers. The model of the traveling wave laser has been extended to include a coupling between the OTDW in the form of a mutual backscattering of energy from each beam into the direction of the other. In addition to predicting frequency lock-in, backscattering provides a mechanism for

strong mode competition between the OTDW.

For steady-state single-mode operation (one pair of OTDW) the fields are represented by the following vectors.

$$\begin{array}{ccc} \overleftarrow{E_2} & \overrightarrow{E_1} & \\ E_2 < \omega_2 t + \varphi_2(t) & E_1 < \omega_1 t + \varphi_1(t) & \\ \overleftarrow{r_1 E_1} & \overrightarrow{r_2 E_2} & \\ r_1 E_1 < \omega_1 t + \varphi_1(t) + \epsilon_1 & r_2 E_2 < \omega_2 t + \varphi_2(t) + \epsilon_2 & \end{array}$$

E_1 , E_2 are the amplitudes of the fields, oscillating at frequencies ω_1 , ω_2 with phases φ_1 , φ_2 respectively. The model assumes a net lumped fraction r_2 , r_1 of fields E_2 , E_1 scattered into the direction of field E_1 , E_2 with an additional phase ϵ_2 , ϵ_1 , respectively. The fields may be represented as in Fig. 1.⁴

*This work was supported by NASA-ERC.

†To be submitted in partial fulfillment of the requirements of the degree Doctor of Philosophy at New York University.