

FIG. 1. Scintillation response of anthracene to surface-incident electrons. Curves (a), (b), (d): computed from surface-escape effects; (a), (b): freshly cleaved surfaces; (d): polished surface of 1 cm^3 scintillation grade crystal. Curve (c): experimental response (Taylor *et al.*).

for internal electrons. Curves (a) and (b) refer to freshly cleaved surfaces; the former was given by a smooth, clear surface and the latter by a translucent surface. Curve (d) was given by a smooth polished surface aged in the dark by exposure to the atmosphere for several months. The very low efficiency of this surface is attributed to chemical deterioration during ageing and is being investigated further. The experimental response curve for surface incident electrons measured by Taylor *et al.* is shown by curve (c); a small correction, about 5%, has been applied to correct for back diffusion of incident electrons.¹⁵ The state of the crystal surface during this measurement is not known but since the crystal was mounted in vacuum

¹⁵ E. J. Sternglass, Phys. Rev. **95**, 345 (1954).

it is probable that sublimation produced a slightly translucent surface which would enhance surface escape effects.

CONCLUSIONS

The scintillation response of anthracene to surface incident electrons is very sensitive to surface effects particularly if the crystal surface is not smooth and freshly cleaved. These effects are due to surface escape of fluorescence and to chemical deterioration of the crystal surface and are sufficient to explain the observed difference in the response of anthracene to internal and external electrons. It is desirable, however, to measure the scintillation response and the fluorescence excitation spectrum for the same crystal surface in order to ascertain the precise part played by surface effects.

Photofluorescence measurements made with *para*-terphenyl show surface effects to be absent. This is as expected since re-absorption in this crystal is negligible. Accordingly, for this material the scintillation response should be the same for internal and external electrons apart from slight differences due to back diffusion of surface incident electrons.

For the heavy particles surface effects must be considered at low energies. For alpha particles absorbed in anthracene they become appreciable at energies less than a few Mev and provide a possible explanation for the saturation of the quantity dL/dX observed at high values of dE/dX .

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Surface Potential and Surface Charge Distribution from Semiconductor Field Effect Measurements

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It is possible from measurements of the change in conductance of a semiconductor with application of an electric field normal to its surface to determine both the electrostatic potential of the surface and the distribution of charge in surface states. Such determinations depend upon the uniqueness of the minimum in conductance which can be observed in these experiments, and its independence of the surface state charge.

MEASUREMENTS of the change in conductance of semiconductor samples with application of a transverse electric field have previously indicated¹ a dependence on the properties of the semiconductor surface. It has recently become apparent that one can obtain from such experiments a direct determination of the surface potential (the electrostatic potential of the surface relative to the interior of the semiconductor) and quantitative information concerning the distri-

¹ W. Shockley and J. L. Pearson, Phys. Rev. **74**, 232 (1948).

tion of charge in nonconducting electron states in the energy gap at the semiconductor surface. The essential feature of these determinations is the recognition that as the surface potential is varied the conductance of the sample will go through a minimum which has a unique value independent of any immobile surface charge. When the minimum is observed experimentally, it serves as a reference by which the measured conductance as a function of the applied electric field can be related to the surface potential and the charge in surface states.

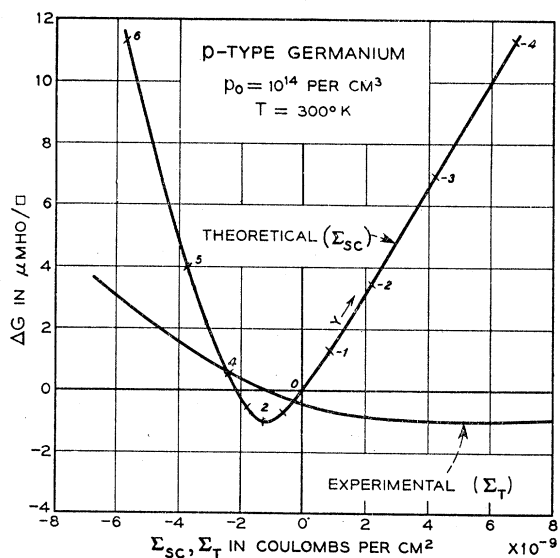


FIG. 1. Theoretical dependence of surface conductance on space charge and experimentally determined dependence on total charge.

The total charge on the semiconductor per unit of surface area is $\Sigma_T = kE/4\pi$, where E is the applied electric field. This is divided as $\Sigma_T = \Sigma_{sc} + \Sigma_s$, where Σ_{sc} is the charge in the space-charge region adjacent to the surface but inside the semiconductor and Σ_s is the charge in surface states, assumed to be immobile. The conductance of the sample depends only upon Σ_{sc} , and one can calculate this dependence as Garrett and Brattain² have done. Such a theoretical curve is shown in Fig. 1 for a high-resistivity p -type germanium sample at 300°K. ΔG is the change in conductance relative to the conductance at $\Sigma_{sc} = 0$. For positive Σ_{sc} , the hole concentration near the surface is increased with a corresponding increase in the sample conductance. For Σ_{sc} small and negative, both the hole concentration and the conductance decrease. For Σ_{sc} large and negative, an inversion layer of high electron concentration is formed at the surface, increasing the conductance again and producing a minimum in the curve. The slopes on the theoretical curve approach μ_p for Σ_{sc} large and positive and μ_n for Σ_{sc} large and negative. (No correction has been applied for reduction in mobility due to constraint of the carriers to a thin surface region. According to Schrieffer's analysis,³ in the particular case considered here the correction would be small.) Indicated along the theoretical curve are values of Y , the surface potential expressed in units of kT/q .

Figure 1 also shows an experimental curve taken with a 180-cps external electric field on an etched sample in dry nitrogen. The abscissa is now Σ_T . The experimental curve has been adjusted *vertically* so that its minimum occurs at the minimum of the theoretical curve. This adjustment is significant since the minimum conductance has a unique value independent of Σ_s . Having made this adjustment, the experimental conductance

² C. G. B. Garrett and W. H. Brattain, Phys. Rev. **99**, 376 (1955).
³ J. R. Schrieffer, Phys. Rev. **94**, 1420 (1954).

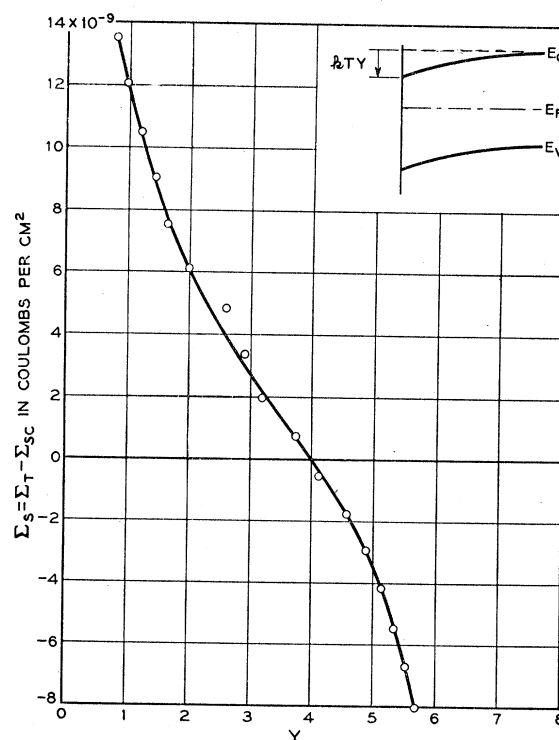


FIG. 2. Charge in surface states as a function of surface potential.

has an absolute significance, in terms of Σ_{sc} and Y . The difference between the experimental and theoretical curves at a given value of ΔG is just Σ_s . Thus by comparing the two curves one can obtain Σ_s as a function of Y . Figure 2 is a plot of this result. As indicated, the surface states are neutral when $Y \approx 4$, i.e., when the Fermi level is about $3kT$ above the middle of the band gap at the surface. (For this sample the Fermi level in the body is about $1kT$ below the middle of the band.) The shape of the curve is related to, but does not uniquely determine, the energy distribution of the surface states. The distribution may be continuous, in which case the slope of the curve is the surface state density involving the minimum number of states; or the distribution may be discrete, perhaps as described by Bardeen and Brattain⁴ in their model of the surface. This latter possibility would predict a curve similar in shape to Fig. 2.

Referring again to Fig. 1 at $\Sigma_T = 0$, the measured conductance indicates a value of $Y = +3$. The chemical state of this surface is such that in the absence of an external electric field it has a surface potential of $+0.08$ volt.

In order to make the foregoing determinations it is essential to obtain the conductance minimum in the experimental curve. This can always be done, at least in principle, with large enough electric fields. Within this limitation, it is thus possible to study the surface potential and the distribution of charge in surface states by field-effect measurements alone.

⁴ W. H. Brattain and J. Bardeen, Bell System Tech. J. **32**, 1 (1953).