

## Properties of Cleaned Germanium Surfaces

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Field effect and conductivity measurements were made on cleaned (111) and (100) germanium surfaces. The surfaces were cleaned by an argon bombardment technique similar to that developed by Farnsworth. The cleaned surfaces were exposed to a modified Brattain-Bardeen ambient cycle and the change in surface properties measured. The cleaned surface data showed that a (100) surface is more highly  $p$  type than a (111) surface, and these results are interpreted qualitatively by an atomistic model.

### INTRODUCTION

THE development of ultra-high vacuum techniques<sup>1</sup> in recent years has made the study of surface properties, free of contaminating influences, a realizable goal. A number of investigators have employed these techniques to study the surface properties of germanium<sup>2-8</sup> and silicon.<sup>9</sup> Two techniques have been used to obtain clean surfaces. The first, developed by Farnsworth and his colleagues,<sup>10</sup> consists of a combination of heat-treatment, argon ion bombardment, and annealing. The second, which has recently been reported, is that of cleaving crystals.<sup>7,8</sup> Different methods are used to measure the physical properties of these surfaces, such as electron diffraction patterns,<sup>3,10,11</sup> work function,<sup>2,6,9</sup> surface conductivity and field effect,<sup>4</sup> and photoconductivity.<sup>2</sup> In general, as a result of most of these measurements, there seems to be an area of general agreement that a cleaned surface has  $p$  type conductivity and is probably degenerate  $p$  type.<sup>2</sup>

The results which are reported in this study were made on cleaned germanium (111) and (100) surfaces, which had been subjected to the argon bombardment cleaning technique. The physical properties of the surfaces are determined by measuring changes in conductivity and field effect when the samples are exposed to contaminating atmospheres, which is similar to a pro-

cedure used by Bardeen and Brattain.<sup>12</sup> The data are qualitatively evaluated in terms of an atomistic model which is based on the number of broken bonds for surface atoms on the (100) and (111) planes of germanium.

### EXPERIMENTAL TECHNIQUE

The sample holder and field probe used in making the measurements are illustrated in Fig. 1. *A* is the sample holder, *B* is the germanium sample, and *C* is the field effect probe. The sample *B* sets on a quartz base *I*. The metal parts of the sample holder, shown cross-hatched, are made of molybdenum. The movable arm of the sample holder *2* is held against the sample by the slight tension in the tungsten spring *3*. The slots *4* illustrate how contact is made between the arms of the sample holder and the sample. Tungsten conduction probes are inserted in the two holes in the quartz shown beneath the sample. The quartz caps *5* cover the molybdenum sample holder and serve to prevent any molybdenum from sputtering on the sample during ion bombardment. The field probe *C*, which can be manipulated by means of an external magnet, consists of a molybdenum inset *6* which fits into a quartz box *7*. The bottom of the quartz box is ultrasonically drilled to a thickness of 0.003 in.-0.004 in. A gold film *8* is deposited on the

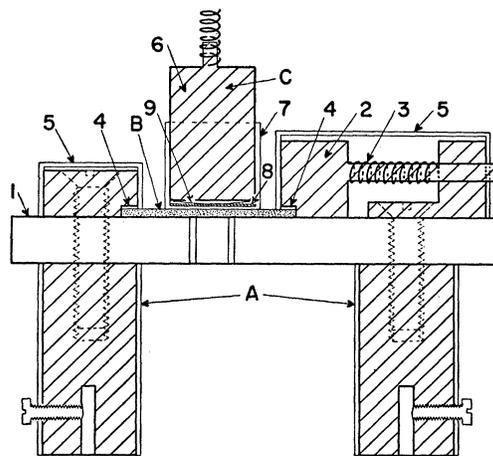


FIG. 1. Cross section of sample holder.

<sup>12</sup> W. A. Brattain and J. Bardeen, *Bell System Tech. J.* **32**, 1 (1953).

<sup>1</sup> D. Alpert, *J. Appl. Phys.* **24**, 860 (1953); R. T. Bayard and D. Alpert, *Rev. Sci. Instr.* **21**, 571 (1950).

<sup>2</sup> J. A. Dillon, Jr., and H. E. Farnsworth, *J. Appl. Phys.* **28**, 174 (1957).

<sup>3</sup> Farnsworth, Schlier, George, and Burger, *J. Appl. Phys.* **29**, 1150 (1958).

<sup>4</sup> P. Handler, *Semiconductor Surface Physics*, edited by R. H. Kingston (University of Pennsylvania Press, Philadelphia, 1957), pp. 23-51.

<sup>5</sup> Robinson, Robinson, and Gatos, *J. Appl. Phys.* **29**, 771 (1958).

<sup>6</sup> F. G. Allen and A. B. Fowler, *J. Phys. Chem. Solids* **3**, 107 (1957).

<sup>7</sup> D. R. Palmer and C. E. Dauenaugh, *Bull. Am. Phys. Soc.* **3**, 138 (1958).

<sup>8</sup> G. A. Barnes and P. C. Banbury, *J. Phys. Chem. Solids* **8**, 111 (1959).

<sup>9</sup> J. A. Dillon and H. E. Farnsworth, *J. Appl. Phys.* **29**, 1195 (1958).

<sup>10</sup> Farnsworth, Schlier, George, and Burger, *J. Appl. Phys.* **26**, 252 (1955).

<sup>11</sup> R. E. Schlier and H. E. Farnsworth, *Semiconductor Surface Physics*, edited by R. H. Kingston (University of Pennsylvania Press, Philadelphia, 1957), pp. 3-22.

bottom of 7 by means of vacuum deposition. A molybdenum leaf spring  $\theta$ , which is 0.001 in thick, makes contact between the molybdenum inset  $\phi$  and the gold deposit  $\delta$ . An ion gun, not shown in this sketch, is mounted in the side-arm of the tube and consists of a tungsten filament and molybdenum anode. Precautions were taken to prevent any tungsten from the hot filament evaporating onto the sample.

The germanium samples were prepared from 46 ohm-cm  $n$  type single crystals. The sample dimensions were  $11 \times 8 \times 0.5$  mm. The crystal orientation was determined by x-rays to an accuracy of 1%. The samples were cut to the correct orientation and dimensions by a diamond saw, polished mechanically with a series of grits down to 4/0, and then etched in CP-4 as a final surface treatment. After a thorough rinsing in distilled water, the sample was dried and mounted in the sample holder.

The vacuum system used in these measurements is illustrated in Fig. 2. The system is pumped by two

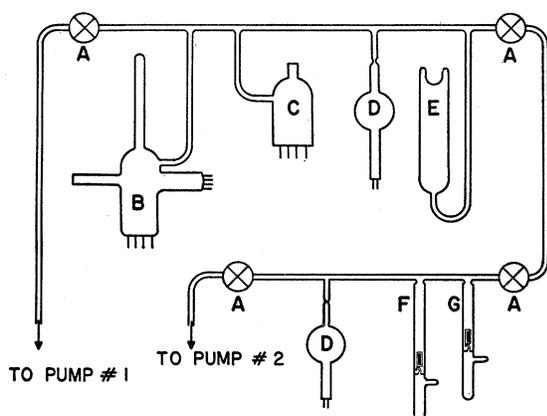


FIG. 2. Schematic of vacuum system.

three-stage oil diffusion pumps, using Octoil S, through individual liquid nitrogen traps. The valves  $A$  are bakable metal high vacuum valves,  $B$  is the tube under test,  $C$  is a Bayard-Alpert type ionization gauge, and  $E$  is a platinum Pirani gauge. The bulbs  $D$  are getter tubes using either titanium or molybdenum as the gettering metal. The gas bottle system is contained between the lower valves in the figure and consists of gas bottles such as  $F$  and  $G$ . The three gases used in this investigation are argon, oxygen, and water-saturated nitrogen. The argon bottle is prepared from liter flasks of reagent grade argon, which is passed over a gettered molybdenum film in an ultra-high vacuum system. The water-saturated nitrogen bottles are prepared by putting a few drops of distilled water into the bottle, evacuating it while the water is cooled by liquid nitrogen, then filling the bottles with nitrogen at 700 mm of mercury. The capacity of the gas bottles is approximately 50 cc. The gases are individually leaked into the system by breaking the break-seal and leaking the gases into the

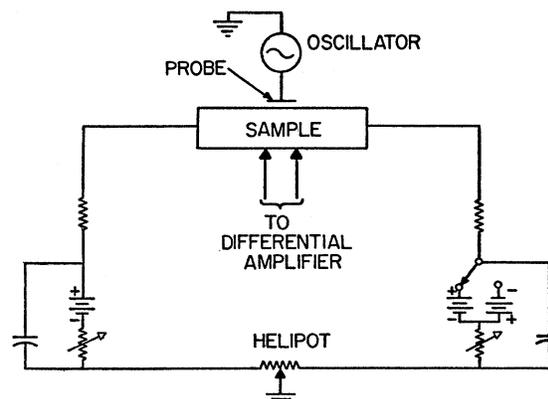


FIG. 3. Circuit for measuring field effect.

main system by means of vacuum valves  $A$ . The whole vacuum system illustrated in Fig. 2 can be baked by an overhead oven at  $400^\circ\text{C}$  and a working vacuum of  $3 \times 10^{-10}$  mm is obtained.

The electrical conductivity was measured by passing current, from a constant current source, through the sample and measuring the voltage across the conduction probes with a potentiometer. The circuit used for measuring the field effect is illustrated in Fig. 3. This is a bridge circuit which is balanced by varying the helipot to ground. The conduction probes are connected to a differential amplifier, which in turn is connected to an oscilloscope in parallel with a wave analyzer. The bridge circuit is initially balanced with the batteries bucking each other. After balance is attained, the switch is thrown putting the batteries in series, and the value of the field effect voltage, which appears across the conduction probes, is measured on the wave analyzer which is peaked at the oscillator frequency. The field effect voltage arises from the factor  $I_0/\Delta g_{\text{SAC}}$ , where  $\Delta g_{\text{SAC}}$  is the change in surface conductance per square due to the applied field at the probe and  $I_0$  is the dc current through the sample. The type of surface conductivity,  $n$  or  $p$  type, is determined by the Lissajous figure on the oscilloscope which compares the phase of the field effect voltage with the input signal of the oscillator.

#### EXPERIMENTAL PROCEDURE

Because the properties of a surface are probably dependent on the argon bombardment procedure employed, it is worthwhile to elaborate on some of the techniques adopted in this experiment. The most suitable schedule outlined by Dillon and Farnsworth<sup>2</sup> included heating the germanium sample to  $650^\circ\text{C}$  for 20 hours. Dillon and Farnsworth adopted their procedure because it duplicated that one which gave the best surfaces in the electron-diffraction experiments.<sup>11</sup> When their technique was tried, it was found that whenever the intrinsic germanium samples were heated above  $500^\circ\text{C}$ , they were thermally converted<sup>13</sup> to a  $p$  type

<sup>13</sup> R. A. Logan, Phys. Rev. **91**, 757 (1953).

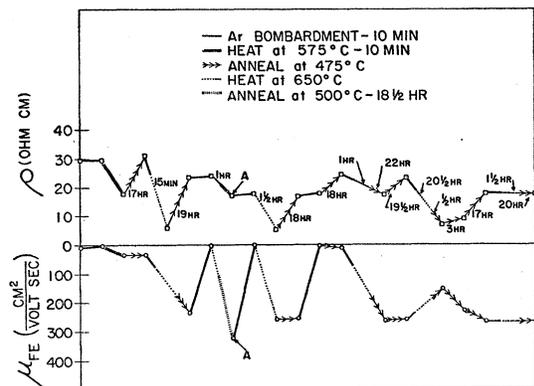


FIG. 4. Resistivity and field effect mobility as a function of the processing procedure for a germanium sample.

sample with a much lower resistivity. This effect decreased the sensitivity of our field effect measurements and was avoided in our preliminary experiments by keeping the sample temperature below 500°C. After further studies with different cleaning procedures, some interesting data, illustrated in Fig. 4, were obtained. Resistivity is plotted as an ordinate on the top scale, measured field effect mobility is plotted as an ordinate on the bottom scale. Field effect mobility, which is defined in the following section, is essentially the mobility of the majority carriers at the surface. The field effect mobility in this curve is *p* type. Each point of this curve represents a measurement after a given procedure. If resistivity and field effect were measured together after a given treatment, the two data points are located at the same point on the horizontal scale. The initial conditions were a sample resistivity of approximately 30 ohm-cm *p* type and a field effect mobility in the range of 20 cm<sup>2</sup>/volt-sec.

A typical cycle may be followed by starting from points "A" in Fig. 4. After argon bombardment, the resistivity is apparently unchanged, but the mobility drops to zero. Heating the germanium to 650°C for 1½ hours radically decreases the resistivity but increases the value of mobility to the order of 270 cm<sup>2</sup>/volt-sec. If this is followed by an anneal at 475°C for 18 hours, the mobility is unchanged and the resistivity is restored approximately to its value at "A". These data and the rest of the data in Fig. 4 are consistent with the following picture. If the surface of the germanium is argon bombarded, it does not seem to affect the resistivity, but the mobility becomes effectively zero. This can be attributed to microscopic surface damage, induced by ion bombardment, which drastically increases the effect of surface scattering. If the sample is now heated to approximately 600°C or above, the mobility increases to a value of hundreds of cm<sup>2</sup>/volt-sec, whereas the resistivity shows a large decrease. The increase in mobility is attributed to a surface annealing of the ion bombardment damage, whereas the degrading in resistivity is caused by thermal conversion of the bulk

germanium.<sup>13</sup> If the germanium is then annealed at temperatures below 500°C, the copper impurity responsible for thermal conversion precipitates out,<sup>14,15</sup> and the resistivity of the material increases, whereas the mobility increases slightly or remains unchanged.

On the basis of these results and the techniques used by Dillon and Farnsworth,<sup>2</sup> the following procedure was adopted as the basic cycle. The surface was argon bombarded at a current density of 100 μa/cm<sup>2</sup>, with a bombarding voltage of 500 volts at an argon pressure of approximately 10<sup>-3</sup> mm, for about ten minutes. This was followed by outgassing the germanium from one to two hours at 650°C. Finally, the sample was annealed at 475°C for a period of 20–40 hours. Four to six of these cycles were employed although there seemed to be no significant changes from cycle to cycle after the first cycle. After this treatment, the samples, which were initially intrinsic, finally became *p* type with a bulk resistivity of 25–30 ohm-cm.

During the last argon bombardment cycle, the argon gas is pumped out of the gas bottle system, shown in Fig. 2, by vacuum pump No. 2. After measurements have been made on the cleaned surface, the getter tubes "D" in Fig. 2 are sealed off the system. With the gas bottle system isolated from pump No. 2 and from the main system by the metal valves, the oxygen bottle is broken and the gas leaked into the main system by the two control valves between the gas bottle system and the tube. The pressure is read on the ionization gauge at low pressure, and on the Pirani gauge at higher pressures. After complete exposure to the oxygen ambient, the oxygen is pumped out and a similar procedure used for introducing the nitrogen saturated with water vapor.

#### EXPERIMENTAL RESULTS AND DISCUSSION

Data obtained on a (100) germanium surface cleaned by the argon bombardment technique are shown in Fig. 5. The upper left-hand ordinate is essentially the conductivity of the sample. The factor  $l/w$  ( $l, w$  = length and width of sample, respectively), which multiplies the conductivity,  $G$ , is inserted so that a change in  $lG/w$ , achieved by varying the surface conditions, can be interpreted as a change in surface conductivity per square of the surface. The lower ordinate in this figure is the field effect mobility. This quantity is obtained from the field effect measurements and is calculated from the formula

$$\mu_{FE} = \Delta g_{sac} / \Delta Q,$$

where  $\Delta g_{sac}$  is the change in surface conductance per square caused by the applied ac probe voltage and  $\Delta Q$  is the surface charge per unit area induced by the probe voltage;  $\Delta Q$  is related to the applied probe voltage and the capacity between the field probe and sample. A

<sup>14</sup> A. G. Tweet, Phys. Rev. **106**, 221 (1957).

<sup>15</sup> A. G. Tweet, Phys. Rev. **111**, 57 (1958).

positive mobility value indicates the majority carriers at the surface are holes and a negative sign indicates that they are electrons.

The abscissa of this figure is time in minutes, and during the interval denoted, indicates the time at a given pressure. The bottom ordinate is  $p$  type field effect mobility. The first three points on this figure show the reproducibility of the cleaned surface data over a period of about 30 minutes. The field effect mobility of the cleaned surface was in the order of 500  $\text{cm}^2/\text{volt-sec}$ . When oxygen is introduced, there is no significant change until a pressure of  $10^{-5}$  mm is reached. At this pressure, the conductivity seems to rise and then drop precipitously with time and pressure. The field effect mobility tends to rise to a maximum and then decreases with time and increasing pressure. After exposure to the full oxygen pressure, the oxygen was pumped out and the surface then exposed to the water-saturated nitrogen. This ambient leads to a further drop in the conductivity, but as can be seen from the mobility data, the surface remained  $p$  type and did not convert to  $n$  type. Attempts were then made to convert the surface to  $n$  type by flowing dry and wet nitrogen over the sample. These data are illustrated by the large squares (conductivity) and large circles (mobility). The symbols  $d$  and  $w$  stand for treatment with dry or wet nitrogen, respectively. As can be seen from the data, the mobility remained  $p$  type throughout the treatment, and the (100) surface could not be converted to  $n$  type by a modified Bardeen-Brattain<sup>12</sup> cycle.

The data of Fig. 5 include the changes on both (100) surfaces of the sample. One of the difficulties inherent in the sample mount, shown in Fig. 1, is the fact that only one surface of the sample is exposed to the argon bombardment. The surface facing the quartz is relatively unaffected. To investigate the influence of this surface, a preliminary experiment was always made on

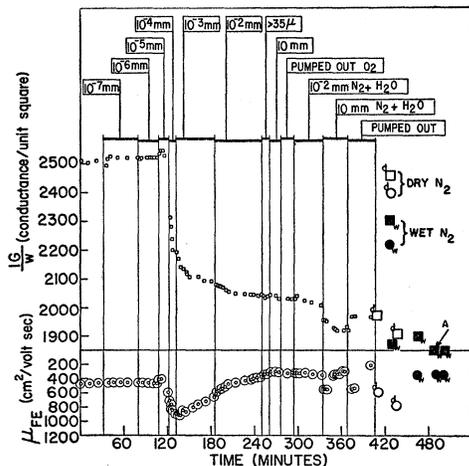


FIG. 5. Conductance/unit square and field effect mobility of a cleaned (100) germanium surface as a function of pressure time exposure to a given ambient.

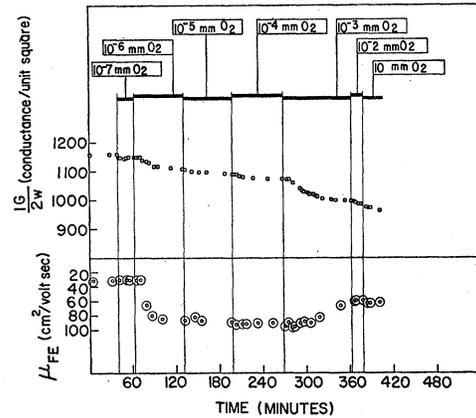


FIG. 6. Conductance/unit square and field effect mobility of a vacuum heat-treated (100) germanium surface as a function of pressure time exposure to oxygen.

all samples before they were cleaned with the argon bombardment technique. Essentially, this preliminary experiment treats the sample in a manner similar to that prescribed for cleaning except no argon bombardment is used. A typical schedule is the following: Initially the sample, tube, and evacuated system are baked at  $400^\circ\text{C}$  for 10–20 hours until a pressure of about  $4 \times 10^{-10}$  mm is attained. The sample is then cyclically heated for two or three cycles with the following schedule: (a) heat at  $650^\circ\text{C}$  for one hour, and (b) anneal at  $475^\circ\text{C}$  for about 20 hours. After this schedule, conductivity and field effect measurements are made on the sample. The three initial points in Fig. 6 illustrate the reproducibility of the measurements before an oxygen ambient is introduced. The coordinates of Fig. 6 are similar to those of Fig. 5, except it should be noted that the magnitude of  $\mu_{FE}$  in Fig. 6 is one-tenth that in Fig. 5. The ordinate  $IG/2w$  is used in Fig. 6 because this is the change in conductivity for one surface, assuming both surfaces are involved in the sample conductivity change and both behave identically when exposed to the ambient. On the basis of these data, the changes in conductivity which can be attributed to the bottom face of the sample, the one not exposed to argon bombardment, can be eliminated from the data of Fig. 5. From Fig. 6 it can be seen that the effect of adding an oxygen ambient was to decrease the total conductance as the pressure increased. The field effect mobility went up with the introduction of the ambient, but the mobility values are quite low.

Figure 7 shows data taken on a (111) surface which has been cleaned by argon bombardment using the procedure outlined in the previous section. The same parameters and notation are used in this curve as are employed in Fig. 5. The field effect mobility is plotted as the ordinate on the right, a positive value denoting hole mobility, a negative value electron mobility. The clean surface data are given as the first four points taken over 45 minutes and are an indication of the

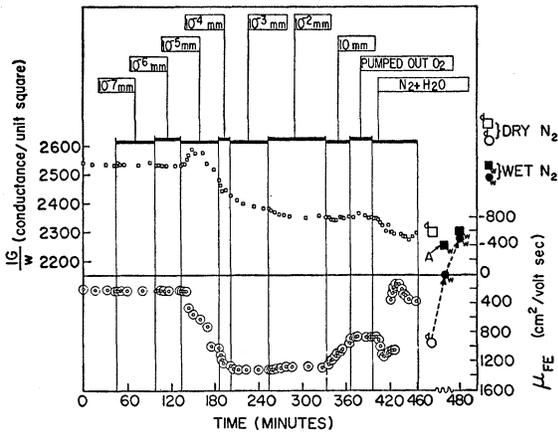


FIG. 7. Conductance/unit square and field effect mobility of a cleaned (111) germanium surface as a function of pressure time exposure to a given ambient.

reproducibility of the data. It should be noted that the mobility of the clean surface is again *p* type and quite high, the order of 200–300 cm<sup>2</sup>/volt-sec. The introduction of oxygen does not make any radical changes in conductance or mobility until a pressure of about 10<sup>-5</sup> mm is reached. At this point, the conductance increases and then decreases with increasing pressure and time. The mobility radically increases at an oxygen pressure of 10<sup>-5</sup> mm of Hg and reaches a value of approximately 1300 cm<sup>2</sup>/volt-sec. After the sample was exposed to the full pressure of the oxygen, the oxygen was pumped out and the sample exposed to an ambient of water-saturated nitrogen. This caused a further decrease in the conductivity and an apparent minimum in the conductance curve, but the mobility readings show that this did not correspond to a surface change from *p* to *n* type because the mobility retained its *p* type character. After this treatment, the sample was then exposed to flowing dry and wet nitrogen ambients, respectively. The large data points have the same meaning in this figure as in Fig. 5. In this case, the data show that the introduction of wet nitrogen gives a true minimum which corresponds to a change in conductivity type at the surface; the field effect mobility for the (111) surface changes correspondingly from *p* to *n* type.

If points "A" in Fig. 5 and Fig. 7 are taken as the zero point in the conductance, and the contribution of the bottom surface of the sample eliminated by means of data of the form shown in Fig. 6, the plots shown in Fig. 8 and Fig. 9 are obtained. The upper ordinate  $\Delta g_s$  in both curves is the change in surface conductance per square of the argon bombarded surface with respect to the minimum conductance point in the experiment. In the case of Fig. 8, for a (100) surface, this minimum is not a true theoretical minimum,<sup>16,17</sup> because the field effect mobility did not change in type in going through

<sup>16</sup> J. R. Schrieffer, Phys. Rev. **97**, 641 (1955).

<sup>17</sup> C. G. B. Garrett and W. H. Brattain, Phys. Rev. **99**, 376 (1955).

the conductance minimum. The zero in Fig. 9 is a true conductance minimum because of the change in mobility type at this conductance value.

The most obvious difference between the data for the (100) surface, Fig. 8, and the (111) surface, Fig. 9, is the much larger conductance change between a clean (100) surface and its minimum, than that for a cleaned (111) surface. The other major difference is that the modified Bardeen-Brattain cycle converted the (111) cleaned *p* type surface to *n* type but was not able to do the same to the (100) surface.

If Schrieffer's theory<sup>16</sup> is extrapolated to calculate the properties of the (111) surface from Fig. 9, using an acceptor density of 10<sup>14</sup>/cm<sup>3</sup>, which is approximately the bulk acceptor density of the sample after argon bombardment treatment, some interesting results are obtained. The results indicate that  $\Delta\psi_s$ , the surface potential, is changed by about 12 *kT* in going from the cleaned surface condition to that at minimum conductance. Figure 10(a) qualitatively shows the bending of the band structure at the (111) cleaned surface, whereas Fig. 10(b) shows the surface energy band structure at the conductance minimum. On the basis of extrapolated theory, the prediction is that, at room temperature, the valence band on a clean (111) surface is within 1 *kT* of the Fermi level. Although this quantitative argument is not completely justified by Schrieffer's theory, which is based on Boltzmann rather than Fermi statistics, one can say qualitatively that the (111) cleaned surface is probably degenerate *p* type.

If the (111) cleaned surface is degenerate *p* type, a comparison of the (111) surface with the conductance change of the (100) surface, in Fig. 8, indicates that the (100) cleaned surface is more highly *p* type. On the basis of the change in  $\Delta g_s$  of approximately 400 micromhos, even though the surface could not be converted from *p* to *n* type by the ambient treatment, the cleaned (100) surface must be highly degenerate *p* type.

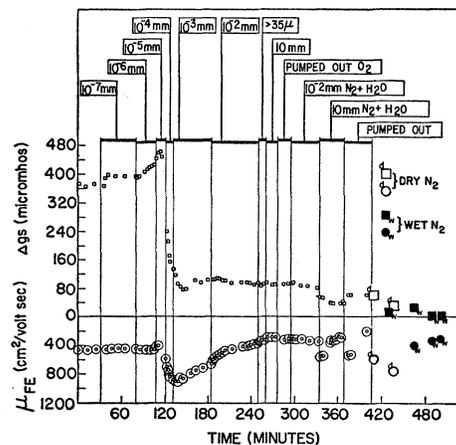


FIG. 8. Field effect mobility and the change in surface conductivity of a cleaned (100) germanium surface as a function of pressure time exposure to a given ambient.

It is interesting to speculate and suggest an atomistic model which seems to explain these results qualitatively. The model assumes that electrons are trapped at unfilled orbital sites associated with broken bonds on surface atoms.<sup>18</sup> To maintain charge neutrality, a free hole must exist in the surface layer for every trapped electron. The free holes are assumed to be responsible for the *p* type character of the cleaned argon bombarded surfaces. On the basis of such a model, it is reasonable to expect the surface properties to be anisotropic. The anisotropic behavior can be attributed to the number of broken bonds associated with a given crystallographic surface, namely one broken bond per surface atom for the (111) and two for the (100) plane.

There are approximately  $7 \times 10^{14}$  surface atoms/cm<sup>2</sup> on a (111) plane. On the basis of one broken bond per surface atom, this leaves a possible electron trap density of  $7 \times 10^{14}$  electron traps/cm<sup>2</sup>. Since Schrieffer's extrapolated theory shows that the (111) surface potential,  $\Delta\psi_s$ , is changed by about  $12 kT$ , in going from the cleaned surface condition to that of minimum conductance, one can calculate the surface charge density for the cleaned surface by extrapolating the results of Kingston and Neustadter.<sup>19</sup> These calculations show that the charge density at the surface is approximately  $10^{12}$  electrons/cm<sup>2</sup>, which would imply that only one electron is trapped for every 700 broken bonds on a cleaned (111) surface.

If this atomistic model is used to interpret the high density of *p* type carriers on a cleaned (100) surface, there would be a greater number of trapped electrons/cm<sup>2</sup> on a (100) germanium surface than on a (111). The population of these traps would be determined by

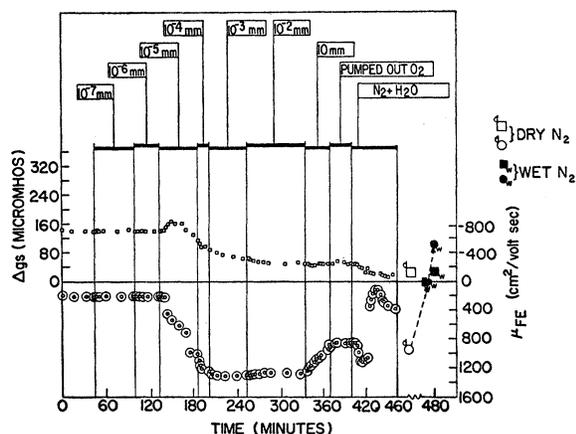


FIG. 9. Field effect mobility and the change in surface conductivity of a cleaned (111) germanium surface as a function of pressure time exposure to a given ambient.

<sup>18</sup> A similar model was originally suggested by W. Shockley for dislocations in diamond-type lattices [W. Shockley, Phys. Rev. **91**, 228 (1953)] and later applied to a surface by Handler (reference 4) and Allen (reference 6).

<sup>19</sup> R. H. Kingston and S. F. Neustadter, J. Appl. Phys. **26**, 718 (1955).

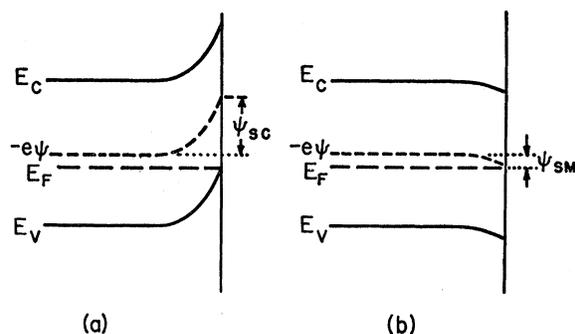


FIG. 10. (a) Energy level diagram of a cleaned germanium (111) surface. (b) Energy level diagram of the surface band structure at the conductance minimum.

two distinct parameters, namely the total number of traps and the ionization energy of the trap. Since these measurements at room temperature cannot distinguish between these parameters, one can only speculate from these data. One partial explanation of the anisotropic behavior of a cleaned germanium surface is that a (100) surface has a larger number of traps available than a (111) because there is a greater number of broken bonds/cm<sup>2</sup> on a (100) than a (111) cleaned surface. In addition, one would also expect the ionization energy of the traps on the two surfaces to be different if this model is valid. From the conductivity data, one would expect the ionization energy for the (100) traps to be lower than the (111).

The most significant information about the mobility data in Figs. 8 and 9 is the large value of mobility for the cleaned surface and the even larger values when oxygen is introduced. Theoretical calculations, using Schrieffer's theory,<sup>20</sup> have been made for a germanium sample with a density of  $10^{14}$  acceptors, and these results show the field effect mobility at the theoretical, cleaned surface to be on the order of 500 cm<sup>2</sup>/volt-sec if the energy bands at the surface are raised  $12 kT$  in going from the conductance minimum to the clean condition. This value is in the same order of magnitude as the observed mobilities in Figs. 8 and 9.

It should be emphasized that the theory used to interpret the data has been extrapolated to a region where its validity is questionable. The only justification for this procedure is that its use in conjunction with the suggested atomistic model offers a possible qualitative explanation for the anisotropic properties of a germanium surface.

## CONCLUSIONS

Measurements similar to those described in this paper have been reported by Handler.<sup>4</sup> Because the technique involved in such an experiment is very exacting, the author believed that a useful purpose would be served

<sup>20</sup> These calculations were made possible through the cooperation of the Electrical Engineering Department of the University of Illinois, who sent us all the necessary computations needed for our calculations.

if the experiment were repeated independently, with some improvement in experimental technique. Special precautions were taken to prevent any possible sputtering from the sample holder to the sample. In addition, the use of metal valves, rather than stopcocks in the gas handling system, is considered an improvement in technique over that used by other investigators.

It will be noted that the general features of Handler's data for a typical surface<sup>4</sup> are similar to those reported here, but the details are considerably different. We have not noted any significant change in clean surface properties during exposure at pressures as low as  $10^{-7}$  mm, but these low pressure measurements on active gases are very difficult to make and hard to interpret.<sup>21</sup> Our field effect measurements on a cleaned surface are much higher than those previously reported. Handler's<sup>4</sup> published data are an order of magnitude lower and Autler<sup>22</sup> and Wallis<sup>23</sup> reported intermediate values for the field

<sup>21</sup> R. E. Schlier, *J. Appl. Phys.* **29**, 1162 (1958).

<sup>22</sup> Autler, McWhorter, and Gebbie, *Bull. Am. Phys. Soc.* **1**, 145 (1956).

<sup>23</sup> P. Handler, *Semiconductor Surface Physics*, edited by R. H.

effect mobility of a cleaned surface. On the basis of the data shown in Fig. 4, the discrepancy between the different published values for the field effect mobility of a cleaned surface can be understood. It is believed that the lower mobility values reported in the literature are associated with an incomplete anneal of the surface damage caused by the argon bombardment cleaning.

In addition, it is believed that the data reported on the anisotropic behavior of the (111) and (100) cleaned surface are one of the first pieces of experimental evidence to indicate the validity of the atomistic model of a cleaned surface as consisting of broken orbital bonds on surface atoms.

#### ACKNOWLEDGMENTS

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Kingston (University of Pennsylvania Press, Philadelphia, 1957), p. 31.

## Aspects of the Theories of Dislocation Mobility and Internal Friction

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The theory of dislocation mobility is reconsidered, and it is concluded that the interaction between thermal waves and a moving vibrating dislocation causes a drag to the first order in  $v/c$ . Modifications of the Seeger-Donth theory for the Bordoni peak are suggested. When account is taken of the diffusion of kinks, general agreement with experiment is obtained. The theory of internal friction in the microwave region is briefly reviewed and discussed. No thorough comparison with experimental data has been performed.

### I. DISLOCATION MOBILITY

A DISLOCATION scatters elastic waves, and in an isotropic distribution of thermal waves a moving dislocation will experience a retarding force proportional to its velocity. This problem was first investigated by Leibfried,<sup>1</sup> who concluded that at room temperature and for ordinary stresses the dislocation velocity would be only a small fraction of the velocity of sound. The Leibfried work was later criticized and extended by Nabarro.<sup>2</sup> Nabarro pointed out that two separate scattering mechanisms should be considered:

(1) Scattering of sound waves by the strained matrix around the dislocation; and (2) Scattered waves radiated from the dislocation vibrating under the action of the impinging waves.

It was concluded that the scattering cross section for mechanism (1) was smaller than the cross section as-

sumed by Leibfried, and that in an isotropic flux of sound waves mechanism (2) does not lead to a drag to the first order in  $v/c$ , where  $v$  = dislocation velocity; and  $c$  = velocity of shear waves.

We shall only reconsider mechanism (2). For the sake of comparison we follow closely parts of the treatment given by Nabarro.<sup>2</sup> Consider the two-dimensional problem of a pure undissociated screw dislocation along the  $y$ -axis in a Cartesian system  $(x, y, z)$ , interacting with shear waves with propagation vectors in the  $x$ - $z$  plane. The solid is assumed to be elastically isotropic.

According to Eshelby,<sup>3</sup> this problem has a complete electromagnetic analogy:

$$\partial u_y / \partial t = H_y / (4\pi\rho)^{1/2}, \quad \sigma_{yz} = -(\mu/4\pi)^{1/2} E_x, \quad \sigma_{xy} = (\mu/4\pi)^{1/2} E_z,$$

$$E_y = H_z = H_x = 0, \quad e = (\mu/4\pi)^{1/2} b,$$

$$\mathbf{F} = e\mathbf{E} + (e/c)\mathbf{v} \times \mathbf{H},$$

<sup>1</sup> G. Leibfried, *Z. Physik* **127**, 344 (1950).

<sup>2</sup> F. R. N. Nabarro, *Proc. Roy. Soc. (London)* **209**, 278 (1951).

<sup>3</sup> J. D. Eshelby, *Solid State Physics* edited by F. Seitz and D. Turnbull (Academic Press, Inc., New York, 1956), Vol. 3.