TABLE I. Position of the quasi-Fermi level at the surface and the total charge in the surface states for various bias voltages (nonsteady-state case).

| | Run *A* | | | Run *B* | |
|---|---|---|---|---|---|
| $V_a$ | $\phi_s$ (volts) | No. electronic charges/cm² $\times 10^{-11}$ | $V_a$ | $\phi_s$ (volts) | No. electronic charges/cm² $\times 10^{-11}$ |
| 4 | 0.175 | 1.76 | 10 | 0.190 | 2.56 |
| 5 | 0.170 | 1.79 | 12 | 0.183 | 2.60 |
| 7 | 0.162 | 1.90 | 14 | 0.175 | 2.63 |
| 10 | 0.146 | 2.07 | 15 | 0.173 | 2.65 |
| 12 | 0.134 | 2.21 | 16 | 0.167 | 2.69 |
| 13 | 0.127 | 2.29 | 18 | 0.156 | 2.76 |
| 14 | 0.115 | 2.36 | 20 | 0.143 | 2.85 |
| 15 | 0.102 | 2.42 | 25 | 0 | 3.10 |
| 16 | 0.095 | 2.49 | | | |
| 17 | 0 | 2.56 | | | |

the valence band. In curves *A* and *B*, the number of these states was $N=1.18\times 10^{11}$ cm$^{-2}$ and $6.90\times 10^{10}$ cm$^{-2}$ respectively. The fit was as good as could be expected. Small $\phi_s$ values had a relatively larger experimental error because the conductances were very low and therefore not accurate. The number of states at the germanium-germanium oxide interface were so low that they could not have been of the Tamm[3] type, in which the number of states correspond exactly to the number of surface atoms (or multiples thereof). The states which were observed must have arisen from impurity atoms or crystalline defects at the surface.

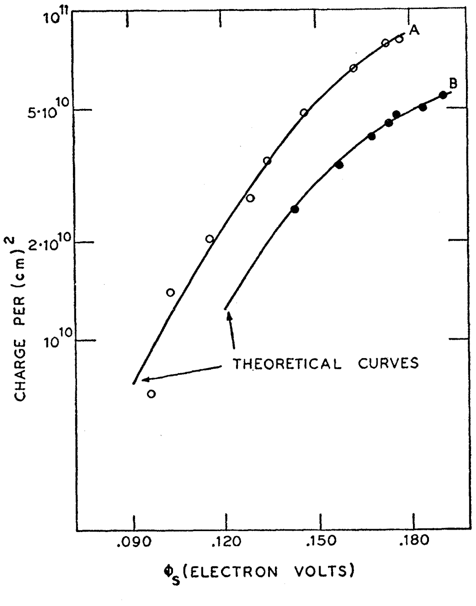

FIG. 3. Charge in surface states at germanium-germanium oxide interface *versus* position of quasi-Fermi level.

The variation of the time constant can be understood qualitatively by assuming that the transfer of electrons from the semiconductor to the traps was hindered by the large potential wall in the oxide film. The electrons had to move into the conduction band of the oxide film. The electric field in the oxide film made the potential wall even higher (see Fig. 1, reference 1). It is obvious that the greater the negative charge outside the oxide and the thicker the film, the higher the barrier. Under steady-state conditions, the charge increased with increasing voltage, and the samples which had been exposed for a longer time to wet $O_2$ and $O_3$ had thicker oxide films. This model is in qualitative agreement with the observed time constants.

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[1] deMars, Statz, and Davis, preceding Letter [Phys. Rev. **98**, 539 (1955)].

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

[3] I. Tamm, Physik. Z. Sowjetunion **1**, 733 (1932).

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# Spin-Lattice Relaxation Time of the Si$^{29}$ Nucleus in Pure Fused Silica

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THE Si$^{29}$ nuclei in a sample of Corning purified fused silica (ultraviolet quality) were observed to approach equilibrium magnetization exponentially in a field of 9.2 kilogauss at room temperature, with a relaxation time of 10 hours. This time is a mean of two measurements which differ by approximately 1 percent. Measurement of the relaxation time in the earth's field at room temperature yielded a value of 1.3 min. An emission spectral analysis at Mellon Institute on a similar Corning sample gave 120–530 parts per million for the summed paramagnetic impurities.

The measurement procedure used was to record the change in magnitude of the component of the macroscopic magnetic moment in the plane of and coincident with the rotating rf field vector. This change was brought about by immersing the sample in the magnetic field for varying time intervals, and made evident using a Bloch crossed-coil and phase-sensitive detection system (a Varian spectrometer) with an rms radiofrequency magnetic field intensity of 1.3 gauss. The shape of the nuclear magnetic resonance curve was indicative of Bloch's limiting case of rapid passage through resonance and did not change when the modulation amplitude was varied from approximately 0.05 to 0.5 rms gauss. Points on the exponential curve used in determining this unusually long relaxation time were obtained by measuring the peak-to-peak value of the recorded signal.

When the magnetic field is maintained at the resonance value and the rf field intensity is of the order of one gauss, the signal becomes undetectable after approximately one minute. Signal intensity is lost considerably faster at lower rf fields.

An investigation of the temperature and field dependence of $T_1$ is now being made, together with a study of the effect of impurities and induced color centers on this relaxation time. Audio-frequency spectroscopy is also contemplated.

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## Resistivity of Dilute Alloys*

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DILUTE substitutional alloys, such as Zn in Cu, have a temperature-independent component to their electrical resistivity which is proportional to the solute concentration. The attempt is usually made[1] to describe the change in resistivity per atomic percent addition, $\rho_0$, with the following parameters,

$$\rho_0 = a(\Delta Z)^2 + b, \tag{1}$$

where $\Delta Z$ is the valence difference between the host material and the substitutional impurity, and where $a$ and $b$ are quantities determined by properties of the two atoms not involving their valence difference; and are generally treated as being independent of position in a given row of the periodic table. It is sometimes considered that this form is made plausible by the existing simple treatments of the dilute alloy problem,[2] in which are treated separately the two cases where (1) a valence difference exists, the scattering potential is taken to be a shielded Coulomb potential, and only the first term in Eq. (1) appears, and (2) the valence difference is zero, and only the second term in Eq. (1) occurs. In cases (1) and (2), the parameters $a$ and $b$, respectively, must of course be positive quantities. Then the argument is made that in general both effects will occur simultaneously, so that one should add the two terms. It seems to have been overlooked that even in the simplest case interference occurs between these two types of scattering, that a linear term in $\Delta Z$ will occur in general, and that in fact it may be expected to be sizable unless one of the other terms is also small.

That this is the case may be seen at once from the procedure of calculating a resistivity change, which is proportional to an average of the square of the matrix element of the scattering potential between the initial and final states:

$$\rho_0 = C\langle (i|V|f)^2 \rangle_{\text{Av}}. \tag{2}$$

(The averaging process involves some angular weighting factors which need not concern us here.) If the scattering potential $V$ contains a term $V_1$ proportional to the valence difference, such as $(e\Delta Z/r)\exp(-qr)$, and also another term $V_2$ independent of $\Delta Z$, determined by inner potentials and lattice strains, the matrix element of $V$ will be equal to the sum of the matrix elements of $V_1$ and $V_2$. Thus the square of the matrix element of $V$ is not given by the sum of the squares of the two parts, as is implied by Eq. (1), but contains an interference term proportional to $\Delta Z$ which may distinguish between atoms of higher and lower valence.

$$(V)^2 = (V_1)^2 + (V_2)^2 + 2(V_1)(V_2). \tag{3}$$

This term [the last in Eq. (3)] has a magnitude at least as great as the smaller of the other two, and may have either sign, so that the interference term may add to or subtract from the resistivity.

Averaging Eq. (3) over angles, we obtain $\langle (V_1)^2 \rangle_{\text{Av}}$ and $\langle (V_2)^2 \rangle_{\text{Av}}$, which correspond to the first two terms in Eq. (1), plus the linear term $2\langle (V_1)(V_2) \rangle_{\text{Av}}$ which may be of either sign. [Since $(V_1)$ and $(V_2)$ will in general have different angular dependences it is possible that the averaging process may tend to decrease the magnitude of the term linear in $\Delta Z$ by accidental cancellation, but this effect may only be investigated in specific cases by explicit calculations of the matrix elements involved.] The point made here is that Eq. (1) is not justified by theoretical arguments, and also that it would be surprising to find it capable of interpreting experimental results.

The writer is indebted to Dr. E. I. Salkowitz for a stimulating conversation on this subject.

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[1] J. Linde, Ann. Phys. **15**, 239 (1932).

[2] N. F. Mott and H. Jones, *The Theory of the Properties of Metals and Alloys* (Oxford University Press, London, 1936), Chap. VII. An extension of these calculations has been performed by D. L. Dexter, Phys. Rev. **87**, 768 (1952). Note, however, that J. Friedel [Phil. Mag. **43**, 153 (1952)] has shown that additional complications sometimes arise so that these simple theories are not always applicable.

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## Resistivity of Dilute Magnesium Alloys

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LINDE'S rule[1] states that for dilute substitutional alloys the increase in specific resistivity of a pure metal due to small alloying additions is equal to a term proportional to the square of the difference in valence of the two elements concerned, plus a second term, or

$$\Delta\rho/A = a\Delta Z^2 + b, \tag{1}$$

where $\Delta\rho/A$ is the increase in specific resistivity per atomic percent addition, $\Delta Z$ is the difference in valence between the solute and solvent atoms, and $a$ and $b$ are constants. For convenience we define $\gamma = \Delta\rho/A$. In Linde's work, the monovalent face-centered-cubic metals, copper, silver, and gold, were the solvents. In these cases, Linde found that the parameters $a$ and $b$