CHANGE OF DISLOCATION VELOCITY WITH FERMI LEVEL IN SILICON

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The electronic environment of dislocations in semiconductors markedly affects their velocities and hence the plasticity of semiconductor crystals.[1] In this note we report direct measurements of the velocity of dislocations in heavily doped n- and p-type silicon, and compare these measurements with velocities in undoped silicon. Velocity measurements were made in the following manner. A scratch was made with a diamond point on a bar of dislocation-free silicon. Dislocation-free crystals were used since grown-in dislocations can move readily under an applied stress and interfere with motion from the scratch. The bar was then etched for about 10-15 sec to remove heavy damage at the scratch, and stressed in three-point bending at elevated temperatures for a given time. This one test gives information on dislocation velocity over a range of stresses. Normally the distance that dislocations have moved from the scratch is revealed by etching.[2] In the case of heavily doped silicon, etching methods are unreliable. To reveal dislocations we have instead used Lang's x-ray topographic method.[3] An inherent advantage of the Lang method is that the complete dislocation loop is revealed. This allows unambiguous identification of the dislocation type (i.e., edge or screw) responsible for the observed motion. For the orientation of specimens used in this work, only screw dislocation velocities were measured.

In Fig. 1 we compare x-ray transmission topographs of undoped and arsenic-doped (10^{19} cm^{-3}) silicon for identical times and stresses at 800°C. The orientation of the bending crystals was such that the dislocations intersecting the surface are screw type, moving on the (111) plane inclined at about 40° to the long axis of the specimen and perpendicular to the $\{1\bar{2}1\}$ bending axis. All the dislocations originate from the scratch, and at low stresses individual loops are clearly resolved. The scratch itself does not appear to influence the motion once the loops have been generated and moved.

Comparing Figs. 1(a) and 1(b), it is evident that at 800°C dislocations have for the same applied stress moved about twice as far in the arsenic-doped silicon as in undoped silicon, $v_{As}/v_i \sim 1.8$ where v_i is the velocity in the undoped crystal. Unfortunately, at these

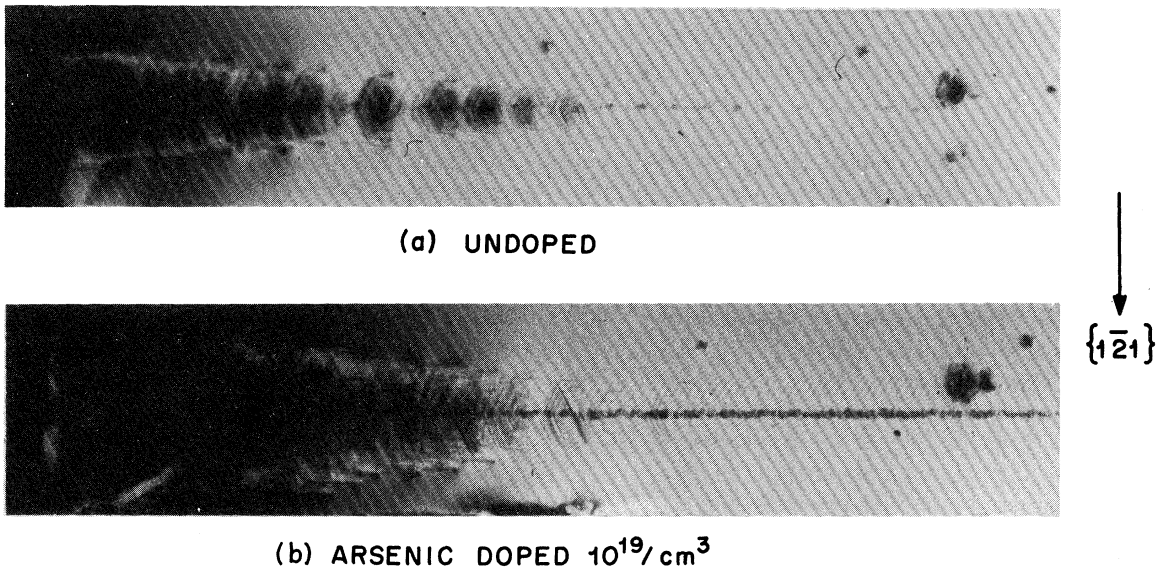

FIG. 1. X-ray topographs showing dislocation motion from a nucleating center and its variation with stress. (a) Undoped silicon. (b) Arsenic-doped (10^{19} cm^{-3}). Both specimens stress $\tau_{max}=3.5$ kg/mm^2 at $T=800$°C for 100 sec.

high temperatures, it was not possible to dope to a high enough concentration with the acceptor gallium to observe an effect on velocity for p silicon. However, at a lower test temperature, crystals with enough gallium can be prepared, so that a decrease in dislocation velocity is observed in comparison with the undoped crystal. In Fig. 2 we show stress-velocity measurements at $T = 600°C$ for screw dislocations. At this temperature the effect for arsenic doping (10^{19} cm^{-3}) has become much greater than at 800°C, $v_{As}/v_i \sim 6$.

For gallium-doped silicon the concentration of impurities that can be incorporated in the crystal is much lower ($<10^{18}$ cm^{-3}) and $v_{Ga}/v_i \sim 0.65$. At both test temperatures, 800 and 600°C, the concentration of impurities has to be comparable with or higher than the intrinsic carrier concentration before any effect on velocity can be observed. The intrinsic carrier concentration n_i is 5×10^{17} cm^{-3} at 600°C and 2.5×10^{18} cm^{-3} at 800°C. For undoped silicon the velocity-stress relation at 600°C follows the form $v = v_0(\tau/\tau_0)^n$, where $n \approx 1.2$ and τ_0 is a stress required to move a dislocation at $v_0 = 1$ cm/sec. Doping does not significantly change the exponent n in the above relation.

A theory to account for the effect of doping on dislocation velocity has been proposed by Frisch and Patel.[4] The predictions of the theory are in good agreement with previous experimental results in germanium. The theory is based on the well-known acceptorlike behavior of dislocations in germanium.[5] It is postulated[4] that the motion (or formation) of kinks predominates at charged dislocation-acceptor sites. Thus any mechanism (chemical doping) that raises the Fermi level by increasing the electron concentration increases the concentration of charged sites, thereby raising either the motion (or formation) of kinks, and hence the dislocation velocity. Conversely, doping with acceptors lowers the Fermi level and the motion (or formation) of kinks, and thus lowers dislocation velocity.

There are at the present time no measurements on the electrical nature of dislocations in silicon. However, based on the above postulate of the theory and in analogy with germanium, we can make the following certain qualitative predictions about the nature of dislocations in silicon:

(1) Dislocations in silicon are acceptors. If dislocations were donors, we would expect an increase in velocity with acceptor doping whereas experimentally the converse is true.

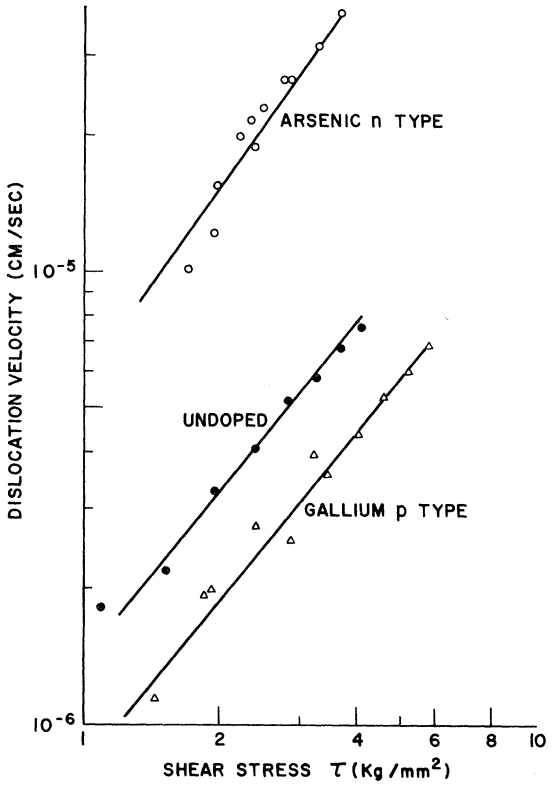

FIG. 2. Screw-dislocation velocity as a function of resolved shear stress. Arsenic doping (10^{19} cm^{-3}) raises and gallium doping (6×10^{17} cm^{-3}) lowers dislocation velocity compared with intrinsic. $T = 600°C$.

(2) The acceptor level, as in germanium, lies above the center of the gap. If the acceptor level were close to the valence band, the levels would certainly be completely occupied, and raising the Fermi level with n-type impurities should have little or no effect on dislocation velocity, whereas our results show that the effects are large. It is possible from the above theory to obtain an estimate of the number of charged sites on a dislocation in the undoped crystal, when the Fermi level (at these high test temperatures) is at the center of the gap. To obtain the necessary parameters for the theory, experiments on the concentration dependence of velocity at constant stress for various temperatures are underway.

Our continued indebtedness to K. E. Benson for supplying us with reliable dislocation-free crystals of special orientation and impurity concentrations is gratefully acknowledged.

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ANISOTROPY IN TUNNELING DENSITY OF STATES IN PURE TYPE-II SUPERCONDUCTORS*

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Recently the density of states in a pure type-II superconductor in the high-field region has been discussed by the Orsay group[1] and by Juranek, Neumann, and Tewordt.[2] In particular, the former pointed out that the excitation spectrum of quasiparticles is strongly anisotropic. The purpose of the present note is to give explicit expressions for the anisotropic density of states, which is experimentally accessible. The angle-dependent density of states is given by

$$N(\omega,\Omega)=\mathrm{Im}\left\{\int\frac{p^2dp}{(2\pi)^3}\frac{1}{\omega-\xi}+\int\frac{p^2dp}{(2\pi)^3}\int\frac{d^3q}{(2\pi)^3}\right.$$
$$\left.\times\left[\frac{1}{\omega-\xi}\frac{1}{\omega+\xi+\vec{v}\cdot\vec{q}}\frac{1}{\omega-\xi}\int d^3r\int d^3r'\Delta(\vec{r})e^{i\vec{q}(\vec{r}-\vec{r}')+i\varphi(\vec{r},\vec{r}')}\Delta^{+}(\vec{r}')\right]\right\}, \tag{1}$$

where

$$\xi=(p^2/2m)-\mu \text{ and } \varphi(\vec{r},\vec{r}')=eH(x+x')(y-y'); \tag{2}$$

ω is the energy of the quasiparticle and Ω is the angular direction of quasiparticle propagation. We take here the field H to be along the z axis. Furthermore, we expand the density of states in powers of the order parameter $\Delta(\vec{r})$, since we are interested in a field region close to H_{c2}. In this region the order parameter is given in terms of Abrikosov's solution,

$$\Delta(\vec{r})=\sum_{n=-\infty}^{\infty}C_n e^{ikny}\exp\left[-eH\left(x-\frac{kn}{2eH}\right)^2\right], \tag{3}$$

where C_n and k are constants.

We can carry out the above integral as given by Cyrot and Maki,[3] and find

$$N(\omega,\Omega)=\frac{N(0)}{4\pi}\left\{1+\frac{\langle|\Delta(\vec{r})|^2\rangle_{\mathrm{Av}}}{2}\int_{-\infty}^{\infty}\rho(\alpha,\Omega)\frac{d\alpha}{(\omega-\alpha)^2}\right\}, \tag{4}$$

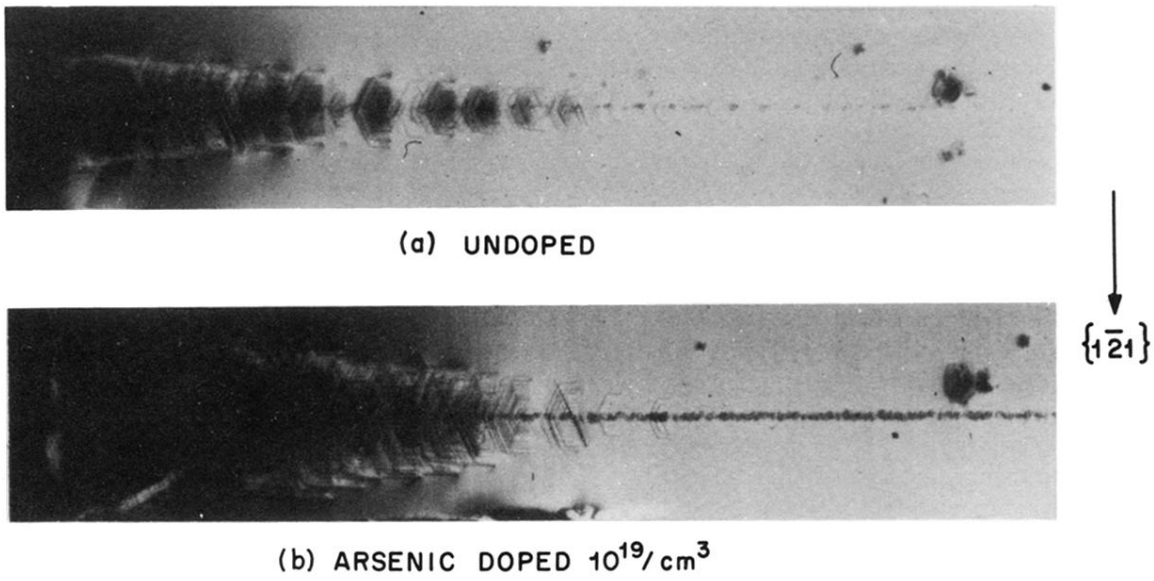
where

$$\rho(\alpha,\Omega)=\frac{1}{\pi^{1/2}\epsilon\sin\theta}\exp\left[-\left(\frac{\alpha}{\epsilon\sin\theta}\right)^2\right]. \tag{5}$$

$\epsilon=v(\frac{1}{2}eH_{c2})^{1/2}$, and v is the Fermi velocity; $N(0)$ is the density of states in the normal metal. Here θ,φ are the polar coordinates for the momentum of a quasiparticle, where the polar axis is taken parallel to the field. It is interesting to note that $N(\omega,\Omega)$ develops no singularity for low frequency (except in the case $\theta=0$) contrary to the case of the total density of states,[1-3]

$$N(\omega)=\int N(\omega,\Omega)d\Omega. \tag{6}$$

This follows from the fact that $\rho(\alpha,\Omega)$ is regular at $\alpha=0$.



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