Drift Velocity of Electrons in Silicon at High Electric Fields from 4.2° to 300°K

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The drift velocity of electrons in silicon at high electric fields is measured in the ⟨111⟩ direction over the range of lattice temperatures from 4.2° to 300°K. It is established that in this range a limiting drift velocity exists. Its temperature dependence is measured. The samples used and the method of measurement are briefly described.

We have measured the drift velocity of electrons at high electric fields in the ⟨111⟩ direction over the range of lattice temperatures from 4.2° to 300°K in samples of high-resistivity silicon. The experiment establishes that at high field strengths and over that range of lattice temperatures, a limiting drift velocity v_l does exist. Its temperature dependence is shown in Fig. 1.

The results have been obtained from the I–V characteristics of pure unipolar space-charge-limited current (sclc). To observe this current, planar structures of the type $n^+\pi n^+$ have been manufactured by masking and diffusion techniques. The starting material was 2 kΩ·cm π-type, but its resisitivity was altered during processing. The base width L of the samples (π-region) is 85 ± 5 μ. The emitter has a diameter of 200 μ. The collector extends over the entire back side of the wafer, which contains a large number of individual structures. Measurements were taken with dc below about 1 mA. Pulse measurements were used above this value to avoid excessive heating. The structures were mounted in a light-tight, vacuum-tight, and electrostatically shielded holder which was placed in a double-dewar cryostat.[1]

A typical display of an I–V characteristic is shown in Fig. 2. The linearity of the characteristic above the threshold voltage V_{th} proves that the drift velocity reaches a limiting value. In that case, a simple model of pure unipolar sclc predicts that the current density j is given by

$$j=2\epsilon\epsilon_0 v_l(V-V_{th})/L^2. \qquad (1)$$

The dielectric constant ϵ is independent of lattice temperature in high-purity silicon.[2] Hence, Fig. 1 is obtained by measuring the change in the slope of j above threshold as a function of lattice temperature and rescaling the ordinate to yield the known value of 1.0×10^7 cm/sec at 300°K.[3] This procedure is adopted to circumvent the uncertainty in the effective area of the geometrically nonsymmetrical device.

This simple interpretation hinges on the assumption that the current observed is indeed pure unipolar sclc. Conclusive evidence is offered in Fig. 2. There, the characteristic is given in a doubly logarithmic plot at 4.2° and 300°K. The solid lines are theoretical curves fitted to the experimental data. At 4.2°K the model assumes the presence of a voltage threshold V_{th}, below which very little current flows (e.g., when traps are present) and above which pure unipolar sclc with constant drift velicity Eq. (1) sets in. At 300°K the model assumes an empirical velocity–field relationship of the form

$$v=v_l\tanh(E/E_0). \qquad (2)$$

E_0 is the electric field at which the low- and the high-field asymptotes to the v–E curve intercept. At intermediate temperatures, a continuous transition from one model to the other is observed.[1] The very good fit obtained between the experiment and the theory at 300°K indicates that the empirical relationship (2) closely describes the true v–E dependence of electrons in silicon. Figure 3 compares this dependence with the results of Norris and Gibbons.[3] Here also, the agreement is good.

Reik and Risken[4] and Jørgensen *et al.*,[5] have analyzed theoretically the limiting drift velocity of electrons in Ge. We have followed the approach of Jørgensen *et al.*, which assumes a Maxwellian distribution of electrons in the valleys and uses a balance-of-energy technique to obtain a solution. In modifying their expression to apply for silicon in the ⟨111⟩ direction, the following approximate relation for v_l results:

$$v_l=[4/(6\pi)^{1/2}]\{(\hbar\omega_0/m^*)[1+(W_1/W_0)\cdot(\omega_1/\omega_0)^2]\}^{1/2}$$
$$\times[(W_{at}/4W_0)(kT/\hbar\omega_0)+(2n_0+1)+(2n_1+1)$$
$$\times(W_1/W_0)\cdot(\omega_1/\omega_0)]^{-1/2}, \qquad (3)$$

where

$$n=[\exp(\hbar\omega)/kT-1]^{-1}.$$

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W, $\hbar\omega$, and m^* are the coupling constant, phonon energy, and effective mass, respectively. The three subscripts 0, 1, and at refer to the intervalley optical, intervalley acoustic, and intravalley transverse acoustic phonons, respectively. The solid line in Fig. 1 illustrates this temperature dependence for the set of parameter values obtained by Long[6] from the temperature dependence of the low-field mobility. The model adequately reproduces the overall temperature dependence of v_l, but not its magnitude. A better fit is obtained by increasing $\hbar\omega_1$ and W_1/W_{at}, and decreasing W_0/W_{at}. The weakness of the temperature dependence of v_l and the uncertainties of the theory cast doubt on the validity and usefulness of such procedure, however.

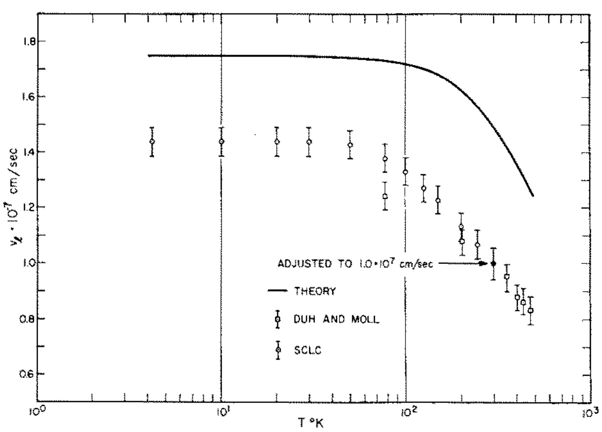

FIG. 1. Temperature dependence of the limiting drift velocity as obtained from the I–V characteristics of sclc, as given by Duh and Moll, and as found from Eq. (3) with the set of parameter values: $\hbar\omega_0=0.0533$ eV, $\hbar\omega_1=0.0163$ eV, $W_0/W_{at}=2.00$, and $W_1/W_{at}=0.15$.

The limiting drift velocity of electrons in silicon has been measured in the same crystallographic orientation by Duh and Moll[7] from 77°–475°K. Their results are given in Fig. 1 as well. Their temperature dependence is somewhat weaker than ours. If real, and attributable to our results, this systematic discrepancy of approximately 15% is most likely to come from the use of Eq. (1). It leaves out the details of the physics at the emitter and collector junctions. To incorporate these details into the model is tedious. Such a modification is also unlikely to significantly affect the overall form of the temperature dependence.

Brown and Jordan[8] have also analyzed pure unipolar sclc of electrons in silicon at 4.2°K, and conclude that $\mu \sim E^{-0.8}$. We re-evaluated their data and concluded

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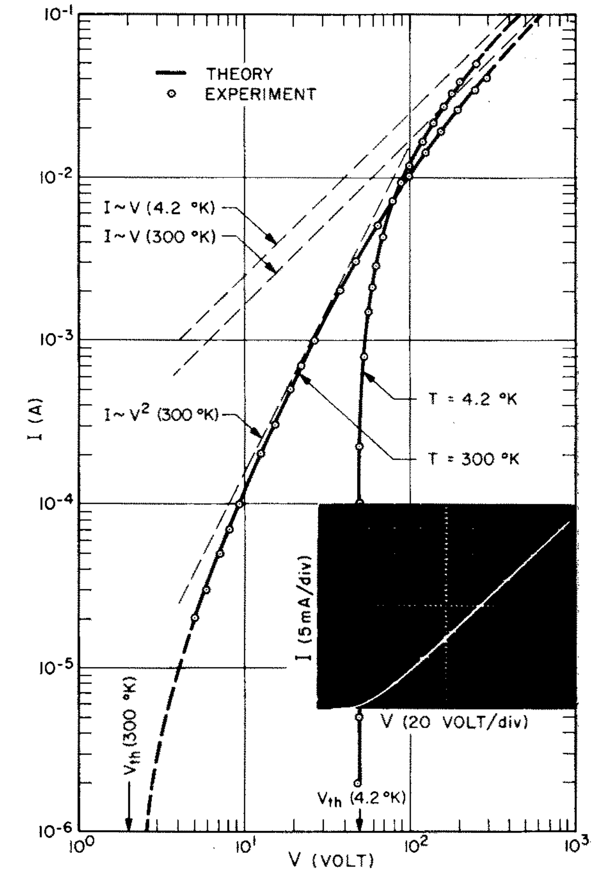

FIG. 2. I–V characteristics of a typical $n^+\pi n^+$ structure at the lattice temperatures 4.2°, 77°K (photograph), and 300°K.

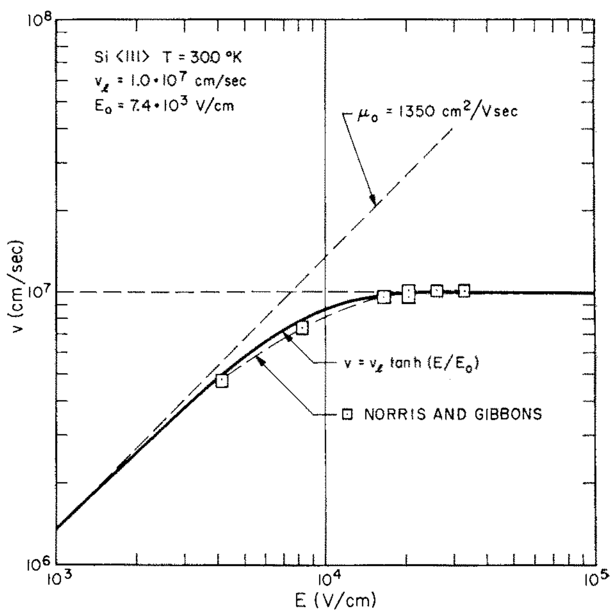

FIG. 3. The velocity–field relationship for electrons in silicon at 300°K as obtained by a time-of-flight technique[3] and from pure unipolar sclc.

that the exponent is unity rather than 0.8 if the effect of a voltage threshold is accounted for properly in their results. This, therefore, offers further evidence that the drift velocity of electrons in silicon reaches a limiting value at high electric fields and low lattice temperatures.

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Epitaxial $BaTiO_3$ on Pt Substrate

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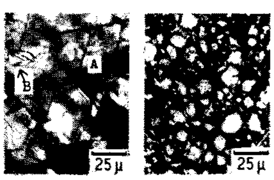
Epitaxial layers of $BaTiO_3$ grow on Pt substrates when: (1) The Pt substrate has preferred orientation $\langle 111 \rangle$; (2) $BaTiO_3$ powder is sintered on this substrate at 1400°C for 24 h in air. The epitaxial $BaTiO_3$ is single crystalline with an orientation of $\{111\}_{BaTiO_3}//\{111\}_{Pt}$ but with a deformation in crystal structure. X-ray diffraction data indicate that the spacing d_{111} is larger by about 1% (0.023 Å) than that of original $BaTiO_3$ which is tetragonal phase at room temperature. The dielectric measurements show that the remanent polarization and the dielectric constant of this specimen are about $\frac{1}{4}$ and $\frac{1}{10}$ values of those of polycrystalline $BaTiO_3$, respectively.

1. INTRODUCTION

It is very important for the fabrication of barium titanate film with excellent dielectric properties to sinter fine-grained $BaTiO_3$ at high temperature (1200°–1400°C) in an oxidizing atmosphere. $BaTiO_3$ films were prepared on the platinum substrates by the sintering method,[1–3] but those films are polycrystalline with grain size of 10–20 μ, and the effect on the crystallization of $BaTiO_3$ on the Pt substrate was not discussed. On the other hand, DeVries reported that very thin



(a) (b)

Fig. 1. Photomicrographs of the film surfaces: (a) specimen F_1; (b) specimen F_2. Both specimens were sintered at 1400°C for 24 h in air. The sintering temperature was kept constant within ±4°C. F_1 and F_2 had approximately the same thickness (~10 μ).

crystals of $BaTiO_3$ were obtained on Pt sheet, and relation between $BaTiO_3$ and Pt was discussed.[4] The specimens, however, were formed in the vapor of KF–$BaTiO_3$ solution at 1000°C, and the lattice constants and dielectric properties were not investigated in detail because of very small specimens. An epitaxial relation between $BaTiO_3$ crystals and Pt substrate was not observed. Though epitaxial films of $BaTiO_3$ were prepared by the method of vacuum deposition, the substrates used in those works to obtain epitaxial $BaTiO_3$ were not Pt but NaCl, LiF, and Au predeposited onto LiF.[5–7]

In this paper, the authors show experimentally that the epitaxial $BaTiO_3$ can be prepared by the sintering

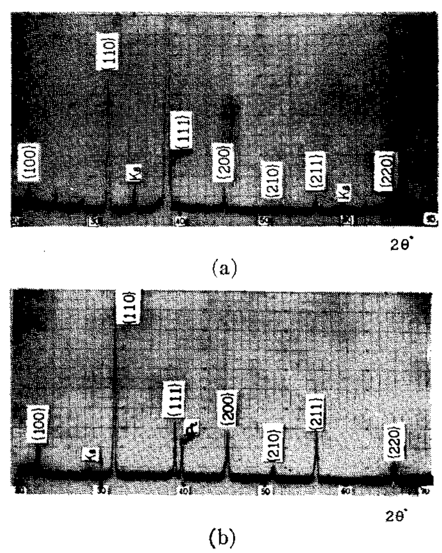


Fig. 2. X-ray diffraction patterns: (a) specimen F_1; (b) specimen F_2. In these measurements Cu-$K\alpha_1$ was used.

method on a Pt (fcc $a_0=3.92$ Å) substrate having preferred orientation $\langle 111 \rangle$, and the interrelation between crystal orientation of $BaTiO_3$ and Pt is clarified.

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