Anisotropy of Critical Field in Low-Temperature Electrical Breakdown in Uncompensated *n*-Type Germanium

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Distinct crystal anisotropy of the critical field in low-temperature electrical breakdown is observed on uncompensated *n*-type germanium having the donor concentration of the order of 10^{16} cm^{-3}. Quantitative agreement is obtained between the theory and the experiments under the assumptions that (1) intervalley scattering of electrons is negligible, (2) collision times in acoustic phonon and in neutral impurity scatterings are isotropic, and (3) conduction electrons lose their kinetic energies mainly through the neutral donor ionization process.

THE crystal anisotropy of the critical field in the low-temperature electrical breakdown has been investigated on uncompensated *n*-type germanium having the donor concentration of the order of 10^{16} cm^{-3}. Single crystals of germanium were grown in the ⟨111⟩ direction by either the Czochralski or the zone leveling method. Arsenic or antimony were doped as donors. No acceptors were doped intentionally. It was found in a preliminary experiment that when the etch pit density was higher than 10^4 cm^{-2}, *V-I* characteristics at 4.2°K became unstable and the values of the critical field, F_c, scattered considerably. The etch-pit density in the crystals used was about 500 cm^{-2}.

These crystals were sliced perpendicular to the growth direction into disks whose thickness was 6∼7 mm. Pellets having various orientations, including [001], [112], [111], and [110], were cut from a disk in a rectangular parallelepiped form (1.5×1.5×1.0 mm^3) (Fig. 1). The number of the pellets for each orientation was about ten. These pellets were sand-blasted with No. 3000 abrasive, followed by chemical etching with a mixture HF(1)+H_2O_2(2)+H_2O(3). The final thickness of the pellets was 0.500±0.005 mm. The accuracy of the orientation angle was confirmed to be within ±0.5°. An electroding material, Pb-Sn-Sb alloy, was evaporated onto both surfaces of the largest area of the pellets (thickness 1 μ), and then alloyed in a hydrogen atmosphere. The diameter of the electrodes was 0.6 mm.

The specimens were dipped in liquid He (4.2°K). Applying dc pulses having various duty cycles, the breakdown voltages were measured on an oscilloscope. In order to check the homogeneity in the impurity distribution in the disk, 10 to 20 other specimens having a particular orientation were also prepared from different portions in the disk. Only the disks were used, in each of which scatter of F_c lay within ±2% for the specimens having the particular orientation.

Typical experimental results on a crystal having the donor concentration of 3×10^{16} cm^{-3} and acceptor concentration of the order of 10^{13} cm^{-3} are shown in Fig. 2. Distinct maxima are observed in the [001] and [111] directions, and minima in the [112] and [110] directions. Substantially the same anisotropy is observed irrespective of the methods of crystal growth and of the kinds of dopants. The texture of the anisotropy curve does not change with the donor concentration in the range of $8\times10^{15}\sim3\times10^{16}$ cm^{-3}.

Theoretical analysis of F_c on the basis of hot electron theory has been reported by Yamashita as follows[1]:

$$e\mu(F_c)F_c^2=\frac{32\,ec^2}{3\pi\mu_a}\left(\frac{T_e}{T}\right)^{1/2}\left(\frac{T_e}{T}-1\right)+S(T_e)E_0\,, \tag{1}$$

$$S(T_e)=2\left(\frac{2\pi kT_e}{m}\right)^{1/2}(\kappa a_0)^2\left(\frac{\Delta E}{kT_e}+1\right)\exp\left(-\frac{\Delta E}{kT_e}\right)(N_D-N_A), \tag{2}$$

and

$$S(T_e)=B_tN_A(=N_A/aT_e)\,. \tag{3}$$

Symbols used here are the same as in the original paper.

In the present experiments, the concentration of donors is three orders of magnitude higher than that of acceptors. At 4.2°K, the neutral impurity scattering mobility, μ_n is estimated to be much smaller than both the ionized impurity scattering mobility, μ_i and the acoustic phonon scattering mobility, μ_a(at $T_e\simeq90$°K). Thus, the electron mobility $\mu(F_c)$ in the left side of

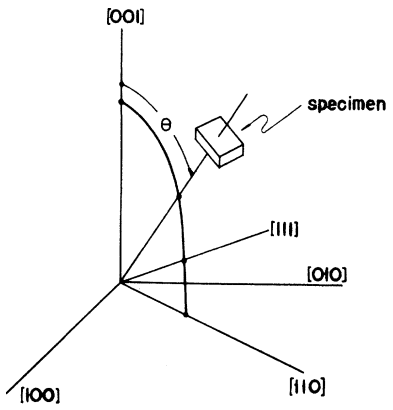

FIG. 1. Schematic diagram of the orientation of specimens.

[1] J. Yamashita, J. Phys. Soc. Japan **16**, 720 (1961).

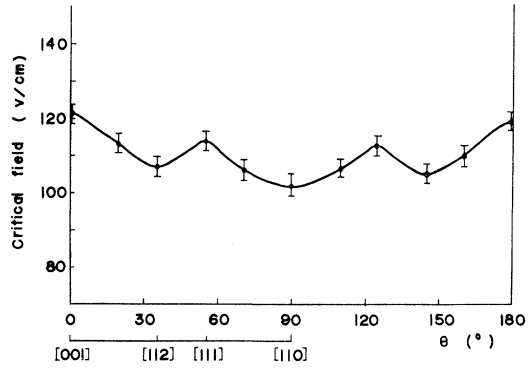

FIG. 2. Crystal anisotropy of F_c.

Eq. (1) may be regarded as μ_n. μ_n and μ_a may be written as $(e\tau_n/m)$ and $(e\tau_a/m)$, respectively, where m is the electron mass, τ_n and τ_a are the collision time in the neutral impurity scattering and that in acoustic phonon scattering, respectively.

By using Eqs. (1)–(3), the values of the critical field for the electrons in each valley of the conduction band are evaluated under the assumptions that the intervalley scattering is negligible and that both τ_n and τ_a are isotropic.[2] The former assumption may be reasonable, because at the critical field the energy transferred from hot to cold valleys due to the intervalley scattering is estimated to be about one-half of the energy loss due to the ionization of neutral donors.[3] The accelerative effective mass of electron, analyzed by Gold,[4] is used as m.

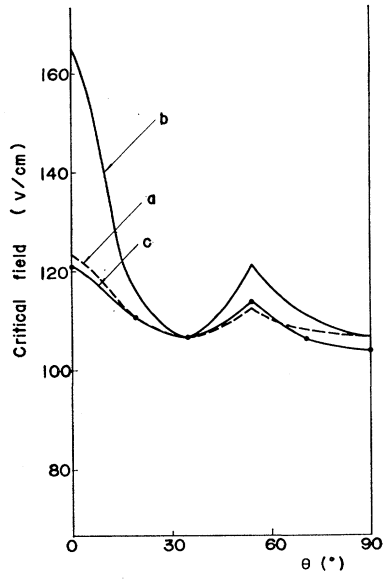

FIG. 3. Crystal anisotropy of F_c. Curve a theoretical curve (energy loss is caused by ionization of neutral donors); b theoretical curve (energy loss is caused by acoustic phonon scattering); and experimental curve.

The variation of calculated values of F_c with the orientation angle is shown in Fig. 3 in comparison with the observed values. The curve a represents the case that electrons lose their kinetic energies through the neutral donor ionization process, that is, the second term of the right side of Eq. (1) is much larger than the first term. While the curve b represents the case that energy loss through the acoustic phonon-scattering process is dominant. The values of B_tN_A are chosen so that the calculated values of F_c may fit the experimental value in the [112] direction. In both cases, the calculated values of F_c in the range $0<\theta<54°44'$ correspond to the critical fields for the electrons in the $[11\bar{1}]$ valley and in the range $54°44'<\theta<90°$ to those in the $[1\bar{1}1]$ and the $[\bar{1}11]$ valleys. The curve a agrees quite well with the observed values. Sclar and Burstein have reported that F_c is proportional to N_D-N_A in the range $N_D-N_A=10^{15}\sim6\times10^{16}$ cm^{-3}, which is reconfirmed by the present author. This fact also suggests that the energy loss caused by the ionization of neutral donors is dominant in this concentration range.

The value of B_tN_A chosen for the curve a is 7.6×10^9 sec^{-1}. Electron temperature T_e at breakdown field is estimated to be 92°K. The recombination cross section of the ionized donor for conduction electrons, σ $(=B_t/v$, v: velocity of electron) is estimated to be order of 10^{-11} cm^2. The large value of σ might be interpreted, if we assume that in a crystal having fairly large concentration of donors, neutral and ionized donors form a center analogous to the hydrogen molecular ions suggested by J. Callaway *et al.*[5]

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[3] G. Weinreich, T. M. Sanders, Jr., and H. G. White, Phys. Rev. **114**, 33 (1959).

[4] L. Gold, Phys. Rev. **104**, 1580 (1956).

[5] J. Callaway and F. W. Cummings, Phys. Rev. **126**, 5 (1962).