Electrical properties of cubic boron nitride

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Boron nitride is a III−V compound and it exists in three modifications: hexagonal (graphite-like and wurtzite) and cubic. The electrical properties of cubic boron nitride have hardly been investigated although it has been reported[1,2] that semiconducting p- and n-type cubic crystals can be prepared and these can be used in the fabrication of rectifying p−n junctions and of BN−diamond heterojunctions. The optical width of the forbidden band of cubic BN is of the order of 6 eV (Ref. 3).

We investigated the electrical conductivity of polycrystalline and single-crystal samples of cubic BN, which was doped with various impurities. At high temperatures we recorded the Hall emf of polycrystalline samples. All samples were synthesized at pressures of 90–110 kbar at temperatures 2200–2500°K using magnesium borides as reaction initiators.[4]

Polycrystalline samples were cylinders with a base diameter of 4 mm and a height of 4 mm. The surfaces were coated by a conducting film, which formed during growth. Before the deposition of contacts, a sample was treated in molten NaOH or KOH at 300°C, which removed the conducting film. Electrical contacts were formed by the deposition, at high temperatures, of silver or nickel contacts or of Aquadag.

The current−voltage characteristics of doped polycrystalline samples were linear and symmetric (for both directions) in the range 1–400 V and they were independent of the contact material. This indicated that the bulk resistance exceeded the contact resistances. The resistivity of the doped samples was within the range 10^7–10^8 Ω · cm.

The current−voltage characteristics of the undoped samples were initially nonlinear up to ~300 V. At higher voltages the characteristics became linear. The resistivity of the undoped samples was 10^{11}–10^{12} Ω · cm.

Cubic boron nitride single crystals were planar twins (combinations of positive and negative tetrahedra) of linear dimensions 200–400 μ and 20–300 μ thick. Gold or aluminum contacts were formed by hot compression. The current−voltage characteristics of single crystals were of the type shown in Fig. 1. The samples doped with silicon or carbon (lines 1 and 2) exhibited a power-law dependence of the current on the voltage $I \propto U^{\alpha}$, where $\alpha = 3/2$. The samples doped with beryllium (lines 3 and 4) exhibited a linear dependence of the current on the voltage; in the case of the sample with the higher resistance (line 3) the application of voltages exceeding 1 V altered this linear dependence into one which obeyed a power law with an exponent of 3/2. The current−voltage characteristics were symmetric for both directions of the current and were independent of the contact material. Since the contacts were made of materials with different work functions (4.8 eV in the case of Au and 3.8–4.2 eV in the case of Al), we concluded that the nonlinearity of the current−voltage characteristics was a bulk property and was associated with the ionization of traps in the forbidden band of cubic boron nitride. The resistivity of various single crystals was within the range 10^7–10^6 Ω · cm.

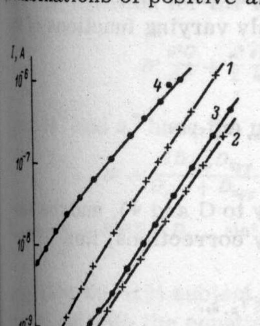

Fig. 1. Current−voltage characteristics of cubic boron nitride single crystals doped with various impurities: 1) Si; 2) C; 3, 4) Be.

Figure 2 shows the temperature dependences of the electrical conductivity of polycrystalline boron nitride. Throughout the investigated temperature range (300–900°K) we observed an activated temperature dependence of the conductivity. We found that the activation energies were 0.23 eV at low temperatures and 0.45 or 0.7 eV at high temperatures (the energies differed from sample to sample).

The temperature dependences of the electrical conductivity of single crystals recorded in the range 100–300°K were exponential and the activation energy varied from sample to sample in the range from 0.09 to 0.17 eV.

For the two most homogeneous (in the electrical sense) polycrystalline samples we were able to measure the Hall effect in the temperature range 500–900°K. These measurements were carried out using a two-frequency method

Fig. 2. Temperature dependence of the electrical conductivity of polycrystalline samples of cubic boron nitride.

and apparatus which enabled us to measure Hall emf's of 100 μV or higher, developed in samples of up to 10^{12} Ω resistance in the temperature range 80–900°K.

In the investigated temperature range the Hall mobility of carriers in cubic boron nitride increased exponentially with rising temperature from 0.2 to 4 $cm^2 \cdot V^{-1} \cdot sec^{-1}$. In the same range the carrier density fell by just one order of magnitude from 10^{14} to 10^{15} cm^{-3}. We were unable to determine the sign of charge carriers.

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Electric pinch effect in layer semiconductors

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It is shown in Ref. 1 that an anisotropic Dember photo-emf due to the macroscopic anisotropy of the sample may appear, under certain conditions, in a layer nondegenerate semiconductor with scalar diffusion coefficients D_p and D_n and hole and electron mobilities $\mu_{p,n} = (e/kT)D_{p,n}$. Unipolar semiconductors at low photoexcitation rates are considered in Ref. 1. Here, we shall consider theoretically the phenomena which accompany the passage of an electric current J through an ambipolar semiconductor whose length is large compared with other dimensions and which has all the characteristic lengths of the problem. As in Ref. 1, we shall assume that the properties of this semiconductor vary periodically along a certain direction ν (Fig. 1), i.e., we shall assume that $D_{p,n} = D_{p,n}(\nu)$, $p_0 = p_0(\nu)$, $n_0 = n_0(\nu)$, and $\psi_{p,n} = \psi_{p,n}(\nu)$, and that the period δ $[D_{p,n}(\nu+\delta) = D_{p,n}(\nu)$, etc.$]$ satisfies the condition

$$\delta \gg l_{d\,\max}, \tag{1}$$

which makes it possible to use the quasineutrality condition

$$p - n = p_0 - n_0 \ll p,\ p_0. \tag{2}$$

Here, p, n and p_0, n_0 are the coordinate-dependent hole and electron densities in the presence of a current J and in a state of thermodynamic equilibrium, respectively; $\psi_{p,n}(\nu)$ is a periodic potential measured in units of kT/e and originating from possible fluctuations of the bottom of the hole ψ_p and electron ψ_n bands; $l_{d\,\max}$ is the highest value of the Debye radius (calculated from the minimum value of p); d is the thickness of the sample (Fig. 1).

At each point, we then have

$$\mathbf{j} = \mathbf{j}_p - \mathbf{j}_n, \tag{3}$$

$$\mathbf{j}_p = -D_p\left[\frac{\partial p}{\partial \mathbf{r}} + p\left(\frac{\partial \psi'}{\partial \mathbf{r}} + \frac{\partial(\psi^0 + \psi_p)}{\partial \mathbf{r}}\right)\right], \tag{4}$$

$$\mathbf{j}_n = -D_n\left[\frac{\partial p}{\partial \mathbf{r}} - p\left(\frac{\partial \psi'}{\partial \mathbf{r}} + \frac{\partial(\psi^0 + \psi_n)}{\partial \mathbf{r}}\right)\right], \tag{5}$$

where ψ^0 and $\psi = \psi' + \psi^0$ are potentials measured in units of kT/e in a state of thermodynamic equilibrium and in the presence of a current J, respectively $[\psi^0(\nu)$, $p_0(\nu)$, and the Fermi level are found in a self-consistent manner from the conditions $j_{p0}\nu(\psi' = 0) = j_{n0}\nu(\psi' = 0) = 0$ and $\int(p_0 - n_0)d\nu = 0]$. In this problem, there are no restrictions on ψ_p or ψ_n or on the amplitude of changes in the density p_0.

We introduce a new variable

$$g = \frac{p}{p_0} \tag{6}$$

and, bearing in mind that $j_{p0}, n_{0}\nu(\psi' = 0) = 0$, we find from Eqs. (4) and (5) that

$$\mathbf{j}_p = -D_p p_0\left(\frac{\partial g}{\partial \mathbf{r}} + g\frac{\partial \psi'}{\partial \mathbf{r}}\right),$$
$$\mathbf{j}_n = -D_n p_0\left(\frac{\partial g}{\partial \mathbf{r}} - g\frac{\partial \psi'}{\partial \mathbf{r}}\right). \tag{7}$$

Since the values of $j_p\nu$, $j_n\nu$, g, and ψ' vary slowly along the direction ν, we shall find these quantities in the form

$$j_{p,\,n\nu} = I_{p,\,n\nu} + j^{(1)}_{p,\,n\nu}\Phi_{p,\,n}(\nu),$$
$$g = G + g_1\Phi_g(\nu),$$
$$\psi' = \Psi + \psi_1\Phi_\psi(\nu), \tag{8}$$

where the first terms on the right-hand sides of the expressions in Eq. (8) are smoothly varying functions of the coordinates

$$I_{p,\,n\nu} = \frac{1}{\delta}\int_{\nu}^{\nu+\delta} j_{p,\,n\nu}(\nu',\tau)\,d\nu' \tag{9}$$

(similar expressions also apply to G and Ψ), and the second terms are small oscillatory corrections, i.e.,

$$|j^{(1)}_{p,\,n\nu}\Phi_{p,\,n\nu}| \ll I_{p,\,n\nu}, \tag{10}$$

$$\int_{\nu}^{\nu+\delta} j^{(1)}_{p,\,n\nu}(\nu',\tau)\,\Phi_{p,\,n\nu}(\nu')\,d\nu' \simeq j^{(1)}_{p,\,n\nu}(\nu,\tau)\int_{\nu}^{\nu+\delta}\Phi_{p,\,n\nu}(\nu')\,d\nu' = 0 \tag{11}$$

[similar expressions apply also to $g_1\Phi_g(\nu)$ and $\psi_1\Phi_\psi(\nu)$].