Superlattices with unoriented barrier layers

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An oriented-growth stimulation effect has been detected on crystal surfaces covered by thin films. Multilayer structures of ultrathin, single-crystal films, which are separated by unoriented layers, have been investigated. The structures have the properties of quantum superlattices.

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It is customary to assume that quantum superlattices can be produced on ideal heterepitaxial structures,[1,2] i.e, those whose individual layers have crystallographic parameters that are very similar. In this paper we discuss a mechanism for oriented growth stimulation of crystals on surfaces covered by unoriented films, which was observed by us, and we give the results of studies of the properties of superlattices of alternating single-crystal and unoriented layers oriented by using this effect.

The potential relief of the field of the surface layer of a single crystal is substantial at distances comparable with the lattice spacing. Therefore, epitaxy is usually observed only on clean surfaces, and a monolayer of disoriented atoms suppresses the process.[3] The fields of only single charges or sufficiently separated charges exist at large distances $L \sim r_D$ (r_D is the Debye radius). If the location of the charges coincides with the lattice sites, then the orienting action of the crystal surface will have an effect at these distances. A system of orienting potentials can be produced artificially by means of an ion stream. If the energy of the ions is such that they pass through the unoriented layer and form vacancy-type defects in the boundary layer of a single crystal, then the surface of the structure will have orienting properties for some length of time that is determined by the lifetime of the defects.

This situation arises when a target is sputtered in a vacuum by a laser beam with an intensity $q > 2 \times 10^8$ W/cm^2. In this case the arrival of most of the evaporated material at the substrate precedes the stream of fast ions with an energy $E_i \sim 10^2 - 10^3$ eV.[4] The location of the maximum of the distribution of interstitial ions with such an energy lies within the limits $L \sim 10$–40 Å for most materials.[5]

TABLE I.

Material of single-crystal film	Material of unoriented layer			
	C	GaAs	Ge	Ta
InSb	25	15	12	10
PbTe	20	12	10	8
CdTe	20	12	10	10

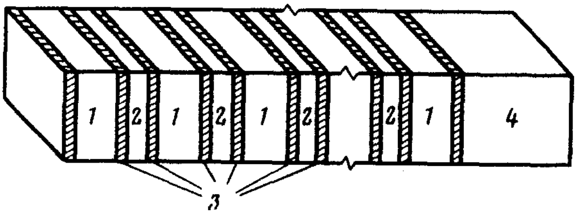

FIG. 1a. Schematic model of a superlattice with a complicated period. 1–single-crystal InSb f films, $L_1 = 100$ (50) Å; 2–single-crystal InSb films, $L_2 = 20$ Å; 3–unoriented GaAs films, $L_3 = 10$–20 Å.

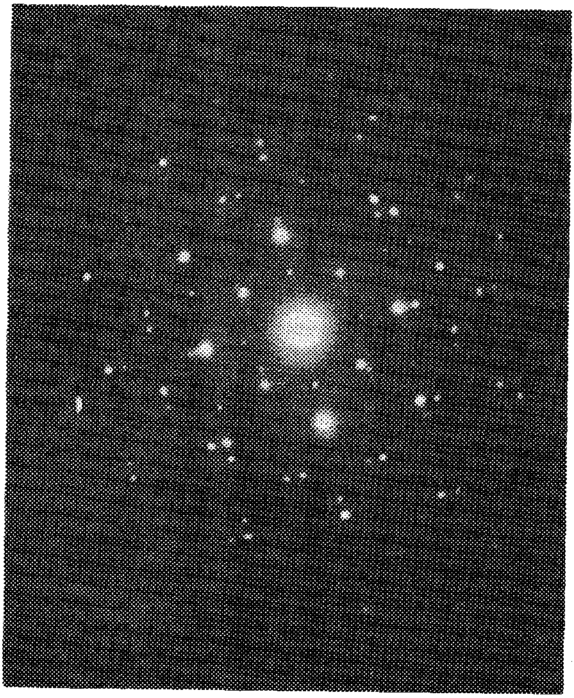

FIG. 1b. Electron-diffraction pattern of periodic (10 periods) homoepitaxial structure of InSb (50 Å) - GaAs (10 Å) - InSb (20 Å) - GaAs (10 Å).

A neodymium laser with the following parameters was used in the experiments: pulse duration $\tau_p \approx 3 \times 10^{-8}$ sec, pulse energy $\leqslant 3$J, and radiation intensity at the target $q \sim 10^8$–5×10^9 W/cm^2. The sputtering was done on naturally occurring, unoriented layers, which were formed during the intermediate steps or as a result of oxidation, and on films of known thickness and composition, which were deposited by the same laser and which cover the surface of a single-crystal substrate. The films formed from the laser plasma become continuous at thickness of a few (3–5) monomolecular layers,[6] because of the high supply rate of the condensate at the substrate. This method was used earlier to produce individual ultrathin continuous films with

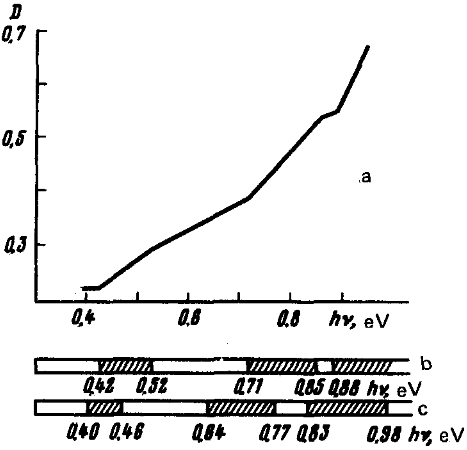

FIG. 2. (a) Spectral dependence of optical absorption; (b) experimental and (c) calculated locationof minibands of a periodic (10 periods) homoepitaxial structure of InSb (50 Å) - GaAs (10 Å) - InSb (20 Å) - GaAs (10 Å).

varying structural perfection, ranging from amorphous to single-crystal films,[7,8] as well as multilayer periodic structures based on them.[9,10] We used Te, Se, GaAs, Ti, Ta, C, As, and Bi as the materials for unoriented layers, i.e., materials that differ both in atomic mass, which determines the penetration depth of fast ions, and also in the conductivity, which is responsible for screening the electrostatic fields. The InSb, CdTe, and PbTe semiconductors served as the materials for the oriented layers. The structure and continuity of ultrathin films were examined by using a type EMV-100AK electron microscope; the microscope resolution was no worse than 8 Å.

In all the cases the oriented growth of the films across the unoriented layers correlated with the presence of a high-energy component in the laser plasma. The maximum thicknesses $L_{\max}$(Å) of the layers, at which epitaxy was observed, are listed in Table I. The thicknesses were estimated from the number of evaporating pulses and from the average film thickness deposited per pulse. The accuracy of this estimate is no worse than 10–15%, as shown by a verification of the dimensional quantization of charge carriers in superlattices and the reflection of x rays from multilayer structures.[9,10]

Multilayer periodic structures of ultrathin (L = 50–100 Å) single-crystal InSb or

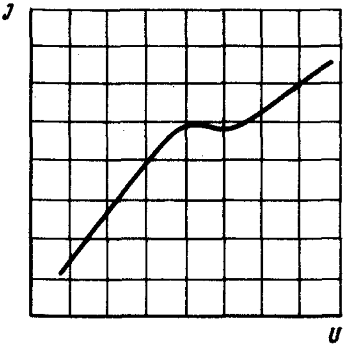

FIG. 3. Static I-V characteristic of a diode on a 10-period InSb superlattice (50 Å) - GaAs (10 Å) - InSb (20 Å) - GaAs (10 Å); 0.5 mA and 0.05 V per division.

PbTe films, separated by unoriented layers of GaAs, C, or Ge with a thickness of 10–20 Å, were obtained by repeating the sputtering cycles. Since barrier layers of such thickness have a high transparency, we used structures with a complicated period (Fig. 1a) in order to reduce the bonding. With such a geometry the thin single-crystal films of the base semiconductor are used as additional barriers. This made it possible to reduce the influence of charge-carrier scattering in the unoriented layers on the properties of the superlattices.

The structural perfection and optical-absorption spectrum of 10-and 20-period superlattices were examined. The I-V characteristics of diodes fabricated from them were measured. The electron-diffraction pattern of a 10-period structure is shown in Fig. 1b. The optical measurements showed that the energy spectrum of the charge carriers has a miniband nature (Fig. 2). The location of the minibands is in good agreement with the results of a calculation using the following dispersion equation:

$$\cos kd = 2\left(\frac{k_1^2 + k_2^2}{2k_1k_2}\right)\sin(k_1L_1)\sin(k_1L_2)\,\mathrm{sh}^2(k_2L_3)$$

$$+\left(\frac{k_1^2 + k_2^2}{2k_1k_2}\right)\sin\{k_1(L_1 + L_2)]\,\mathrm{sh}(2k_2L_3) + \cos[k_1(L_1 + L_2)]\,\mathrm{ch}(2k_2L_3),$$

where L_1 and L_2 are the thicknesses of the layers that form the potential wells, L_3 is the thickness of the barrier layers, $d = L_1 + L_2 + 2L_3$ is the period of the superlattice,

$$k_1 = \left[\frac{2m_1^*}{\hbar^2}E\left(1 + \frac{E}{E_{g_1}}\right)\right]^{1/2}, \qquad k_2 = \left[\frac{2m_2^*}{\hbar^2}(V_0 - E)\left(1 - \frac{V_0 - E}{E_{g_2}}\right)\right]^{1/2}$$

m_1^* and m_2^*, E_{g_1} and E_{g_2} are the effective masses of the charge carriers and the forbidden-band gaps of the materials of the conducting (with the subscript 1) and barrier (with the subscript 2) layers, and V_0 is the barrier height. Negative-resistance regions were observed on the static I-V characteristics (Fig. 3).

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