A. P. Silin. *Semiconductor superlattices.* Solid state structures having, in addition to the periodic potential of the crystal lattice, an additional one-dimensional potential the period of which significantly exceeds the lattice period, are usually called superlattices.

Superlattices are a new type of semiconductors characterized by the presence of a large number of energy bands, having very large anisotropy (they are practically two-dimensional). For the first time such systems were studied by Keldysh in 1962.[1] The properties of semiconductor superlattices are presented at some length in the review articles of Refs. 2–5 and the monographs of Refs. 6–7.

The rapid growth both of theoretical and experimental interest in superlattices is related to the latest achievements of the technology based on the molecular-beam epitaxy in ultra-high vacuum, metallo-organic epitaxy from the gas phase, and other methods. A low temperature of an epitaxy and a low growth rate (~ 1 Å/sec) allow one to achieve atomic smoothness of the interface, and to grow superlattices of high quality.

Physical properties of semiconductor superlattices are determined by their electronic spectra. While the motion of the charge carriers perpendicular to the superlattice axis is free, the motion along the superlattice axis (z) will have a mini-band character.

Compound superlattices of type I (Fig. 1) constitute such periodic alternation of the layers of two semiconductors of thickness $d_{\rm I}$ and $d_{\rm II}$ and with energy gaps $E_{\rm G}^{(\rm I)}$ and $E_{\rm G}^{(\rm II)}$, which gives rise to a periodic system of quantum wells for electrons and holes (type I semiconductors), separated from each other by quantum barriers.

The energy spectrum of electrons in compound super-

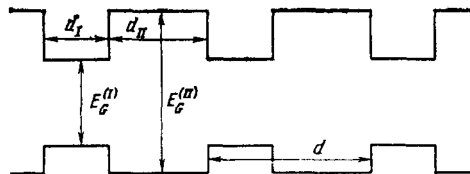

FIG. 1

lattices of type I has the following form:

$$E_{c,j}(\mathbf{p})=\frac{p_{\perp}^{2}}{2m_{c}}+E_{c,j}(d_{I})+E_{c,j}(p_{z},d_{II}), \quad (1)$$

where $E_{i,j}(d_I)$ is the position of the bottom of an energy miniband, which is determined mainly by the width of the quantum well d_I; for lowest minibands

$$E_{c,j}(d_{I})\approx\frac{\hbar^{2}\pi^{2}}{2m_{c}d_{I_j}^{2}}, \quad (2)$$

where $E_{c,i}(p_z,d_{II})$ is the dispersion of the energy minibands, which in the strong coupling approximation has the following form:

$$E_{c,j}(p_{z},d_{II})=-\Delta_{c,j}(d_{II})\cos\frac{p_{z}d}{\hbar}, \quad (3)$$

where $|\Delta_{c,j}(d_{II})|$ is the width of the jth miniband, d is the superlattice period. With the increase of the miniband number its width increases, and the width of the energy minigap decreases. By varying the width of the quantum well d_I it is possible to find the required position of the miniband $E_{c,j}(d_I)$, and by varying the barrier width d_{II}—the width of the miniband $|^{\Delta_{c,j}(d_{II})}$.

If the width of a quantum well becomes comparable to or smaller than the Bohr radius of an exciton in a bulk semiconductor, then, because of the spatial confinement, the binding energy of the exciton increases. Due to the increase in binding energy, excitons in such superlattices can be observed at higher temperatures, including room temperature. The spatial confinement manifests itself also in the fact that the emission and absorption spectra of type I compound superlattices are determined mainly by free excitons, and not by impurities[8], and also by the anomalously large Stark effect.[9]

Of special interest for the study of transport properties are modulation-doped type I superlattices, in which only the layers of the semiconductor with the wider energy band are doped. The ionized impurity centers and the charge carriers generated by them which move to the layers of the semiconductor with a narrower energy gap are spatially separated. As a result, the strong doping of some layers leads to significant change in concentration of free carriers in others, almost without changing their mobility.

In a strong constant electric field E_z, directed parallel to the axis of a superlattice, the motion of charge carriers is confined-they undergo vibrations with a Stark frequency $\Omega = eE_z d/\hbar$, and the current is equal to zero. This behavior of charge carriers can be easily explained by the fact that in the periodic potential of a superlattice the motion energy of charge carriers along the axis of the superlattice, given by expression (3), and, therefore, the velocity $v_z = dE_{c,j}/dp_z$, oscillate with the period $2\pi/\Omega$.[10]

The small dimensions of the regions to which the charge carriers are confined in the coordinate and momentum space lead to a strong nonlinearity in superlattice conductivity in particular, to a negative differential conductivity already for weak electric fields.

In compound type II superlattices, the peak of the valence band of one semiconductor (GaSb) has a higher ener-

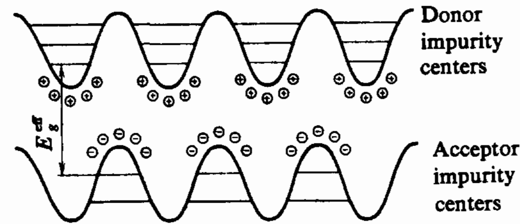

FIG. 2

gy than the bottom of the conductivity band of another semiconductor (InAs), and for this reason a flow of electrons from the valence band of GaSb into the conductivity band of InAs occurs.

However, if the thickness of the layers of this superlattice is sufficiently small, the quantization of charge carriers which depends on the layer size, may lead to the transition from a semimetal into a semiconductor state.[3]

Significant improvement in spatial (on the atomic scale) control over the doping during the growth process of films by the method of molecular-beam epitaxy has made it possible to grow doped superlattices, i.e., periodically alternating thin layers of GaAs of n- and p-types. The superlattice potential is created only by the spatial distribution of the charge (Fig. 2).

An important characteristic of doped superlattices is that the extrema of wave functions of electrons are shifted by half a period of a superlattice relative to the extrema of the wave functions of holes. For this reason, the effective energy gap E_g^{eff} is not rectilinear in coordinate space. By choosing the parameters of a doped superlattice, it is possible to make the recombination times of charge carriers extremely long, since the overlap of the wave functions can be made very small.[4] The large lifetimes allow one to vary easily the concentration of charge carriers.

In addition to the compound and doped superlattices considered above, stressed superlattices with a large mismatch (1–5%) of lattice constants, and amorphous compound and doped superlattices (see, for example, Ref. 5) were also synthesized.

Superlattices provide a unique opportunity to change, in a practically arbitrary manner their energy band structure (band engineering). This allows one, in particular, to change greatly their transport and optical properties and to create, using them as the basis, low-noise avalanche photodiodes, photomultipliers, fast-acting devices, and photodetectors.[11] In addition, semiconductor superlattices are already used for the desgin of a new generation of light-emitting devices, which are easier to manufacture and more efficient than the presently used LED.[12]

[1] L. V. Keldysh, Fiz. Tverd. Tela (Leningrad) **4**, 2265 (1962) [Sov. Phys. Solid State **4**, 1658 (1962)].
[2] A. Ya. Shick, Fiz. Tekh. Poluprovodn. **8**, 1841 (1974) [Sov. Phys. Semicond. **8**, 1195 (1975).
[3] L. Esaki, Lect. Notes Phys. **133**, 302 (1980).
[4] K. Ploog and G. H. Dohler, Adv. Phys. **32**, 285 (1983).
[5] A. P. Silin, Usp. Fiz. Nauk **147**, 485 (1985) [Sov. Phys. Usp. **28**, 972 (1985)].

[6]*Two-dimensional Systems, Heterostructures, and Superlattices*; Berlin; Heidelberg; New York; Tokyo; Springer-Verlag, 1984, (Springer Series in Solid-State Physics, v. 53).
[7]Mnogosloĭnyye poluprovodnikovyye struktury i sverkhreshetki (Multilayer semiconductor structures and superlattices), Gor'kii, IPF ANSSSR, 1984.
[8]C. Weisbuch, R. C. Miller, R. Dingle, A. C. Gossart, W. Wegmann, Solid State Commun. **37**, 219 (1981).
[9]D. A. Miller, D. S. Chemla, T. C. Damen, A. C. Gossard, W. Wiegmann, T. H. Wood, C. A. Burrus, Phys. Rev. Lett. **54**, 2173 (1984).
[10]L. V. Keldysh, Zh. Eksp. Teor. Fiz. **43**, 661 (1962) [Sov. Phys. JETP **16**, 471 (1963)].
[11]F. Capasso, Physica, **B129**, 92 (1985).
[12]D. Bimberg, J. Christen, and A. Stecenborn, in ref. 6, p. 136.