Theory of enriched layer at the surface of a narrow-gap semiconductor

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The nonparabolic nature of the conduction band causes the two-dimensional subbands in the enriched layer at the surface of a degenerate semiconductor to be filled in a certain way.

The energy spectrum of quasi-two-dimensional electrons in the inversion layer and in the enriched layer is determined by the functional dependence $E_i(p_{\parallel})$, where i is the number of the two-dimensional subband, and $p_{\parallel}$ is a two-dimensional quasimomentum. In the case of semiconductors whose chemical potential of the electrons is $\mu < 0$ (all the energies are reckoned from the bottom of the conduction band in the bulk of the semiconductor), the problem of the filling of two-dimensional subbands with electrons at zero temperature is solved simply: Only those states are filled for which

$$E_i(p_{\parallel}) < \mu . \qquad (1)$$

An important point here is that the filling of the ith subband as the surface curvature of the bands increases in this case begins from the bottom ($p_{\parallel} = 0$) at the time the following condition is satisfied:

$$E_i(p_{\parallel}) = \mu ,$$

regardless of the nonparabolic state of the conduction band. This situation for semiconductors with $\mu < 0$ is in good agreement with the data of many experiments.[1]

The situation is quite different in an enriched layer at the surface of a semiconductor with $\mu > 0$. In this case condition (1) also must hold if the state with the energy $E_i(p_{\parallel})$ is to be occupied. But here the question whether this state is localized in the potential well near the surface or whether it corresponds to the infinite motion in the direction perpendicular to the $z = 0$ face of the semiconductor remains unresolved. If the condition for the onset of the filling of the ith subband is used in the form[2]

$$E_i(p_{\parallel}) = 0 , \qquad (2)$$

it would usually lead to an abrupt change in the density of the bound carriers as the next subband begins to be filled.

In the case of a degenerate narrow-gap semiconductor, a regular subband actually begins to be filled when the surface curvature of the bands is much smaller than that following from (2), and the carrier density of the subband increases continuously.

To clearly see this situation, we will consider a case in which the bands are bent slightly and the potential electron energy $V(z)$ satisfies the condition

$$|V(z)| \ll E_g\,(1 + E_{\parallel}/E_g). \tag{3}$$

Here E_g is the width of the band gap, and $E_{\parallel}$ for the standard Kane model is given by

$$E_{\parallel}\,(1 + E_{\parallel}/E_g) = p_{\parallel}^2/(2m),$$

where m is the effective mass at the bottom of the conduction band. If condition (3) is satisfied, it is easy to show that for a fixed $p_{\parallel}$ the existence of the ith bound state in the potential $V(z)$ is determined in a semiclassical approximation by the condition

$$\int_0^{\infty} |V(z)|^{1/2}\,dz > \pi\hbar\,[\,2m\,(1 + E_{\parallel}/E_g)]^{-1/2}\,(i + 3/4). \tag{4}$$

In the case of a parabolic band ($E_g \to \infty$), condition (4) does not depend on $p_{\parallel}$ and is equivalent to (2).

If the finite magnitude of E_g is taken into account, this condition is satisfied more easily as $p_{\parallel}$ is increased. It thus follows that the ith subband begins to be filled with the states having the largest $p_{\parallel}$ at which $E_{\parallel} < \mu$; i.e., with $p_{\parallel} = p_F$, where p_F is the Fermi momentum in the bulk of the material. As the surface curvature of the bands continues to increase, the filling continues due to the states with $p_{\parallel} > p_F$ and the states with $p_{\parallel} < p_F$, which become bound states in the layer near the surface. The carrier density of the subband in this case will increase continuously from the initial zero value, although the Fermi momentum measured from the magnetic oscillation period[2] will be $p_i > p_F$ for this subband.

These particular features of the filling of two-dimensional subbands apply in the case of a pronounced surface bending of the bands. They also apply regardless of whether the semiclassical approximation can be used. These features must be taken into account in order to insure correct interpretation of the experimental data obtained in the study of the properties of quasi-two-dimensional electrons at the surface of the narrow-gap semiconductors. We are basically referring to the experimental results on the characteristics of the enriched layer near the surface curvature of the bands near the point where the regular two-dimensional subband begins.

[1] T. Ando, A. B. Fowler, and F. Stern, Rev. Mod. Phys. **54**, 563 (1982).
[2] V. F. Radantsev, T. I. Deryabina, L. P. Zverev *et al.*, Zh. Eksp. Teor. Fiz. **91**, 1016 (1986) [Sov. Phys. JETP **64**, 598 (1986)].

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