Interpretation of the oscillations of the longitudinal conductivity corresponding to a two-dimensional impurity band

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Because of a correlation in the positions of charged centers, a system which has not had time to complete a structural change during the nonequilibrium filling of an impurity band may complete the structural change through the formation of a superstructure. If the external voltage is varied smoothly, the effect can give rise to oscillations in the rate at which the impurity band is filled, in the band curvature of the semiconductor, and in the surface conductivity.

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Pepper[1] measured the longitudinal conductivity corresponding to a two-dimensional band in an n-type GaAs film in a p–n structure with a metal gate, which produced a Schottky barrier in the n-type film. The band diagram of this structure is shown in Fig. 1. At low temperatures ($T \leqslant 4.2$ K), oscillations were observed in the current as a function of the gate voltage (V_g). Similar oscillations were subsequently observed in a silicon metal-insulator-semiconductor transistor with a high concentration of Na^+ ions near the Si–SiO_2 interface.[2]

We wish to point out that oscillations may appear in the band curvature of a semiconductor if there is a correlation among the charged centers on its surface. A correlation in the arrangement of charged centers also gives rise to a Coulomb gap in the state density[3,4] and a nonmonotonic dependence of the Fermi level on the filling of the impurity band.[5,6]

The equilibrium situation was studied in Refs. 5 and 6. At low temperatures, however, the filling may be essentially a non-equilibrium process because of the long

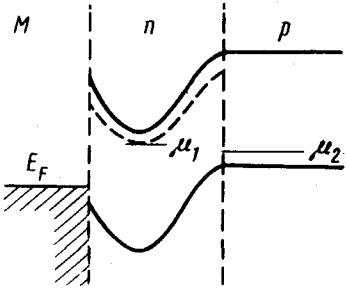

FIG. 1. Energy diagram of a metal-(n-p-junction) structure. μ_1, μ_2—Fermi levels in the n-type channel and the p-type region, respectively. Here $\mu_1 - E_F = qV_g$ and $\mu_1 - \mu_2 = qV_{sub}$, where V_g and V_{sub} are the voltages on the gate and substrate, respectively.

times required for changes in the correlation structure.

Let us examine the filling of impurity centers, taking into account the Coulomb interaction between the localized charges, with a charge exchange resulting from the exchange of electrons with the conduction band. We assume that there is a lattice of charged centers in the impurity band. The state density will then have a gap between empty and filled states, and at equilibrium the Fermi level will be in this gap.

As the external voltage is increased, the system leaves equilibrium. The equilibrium filling of the centers and their charge exchange occur after the attainment of an activation energy equal to the ionization energy of the impurity centers. At a low temperature the lattice thus cannot complete the structural change, and the Fermi quasilevel will rise with increasing V_g without a change in the filling of the impurity band. We are actually assuming that there is a quasiequilibrium electron distribution in the conduction band as a result of a rapid exchange of electrons between the semiconductor and its contacts (the drain and the source). The characteristic time here is the transit time, 10^{-7}–10^{-8} s for the structure of Ref. 1.

Beginning at a certain V_g, electrons are rapidly captured by impurity centers at the minima of the potential, where the electron concentration is at a maximum. A captured electron causes a curvature of the conduction band in its vicinity, and the potential near this electron (in particular, at the minima) increases by an amount $q^2/\epsilon r$, where r is the distance from the newly captured electron. The next electron can be captured only outside a region whose radius r_c is determined by $q^2/\epsilon r_c \simeq 3kT$. The correlation in the positions of the charged centers gives rise to a certain number of states $N_1 = 1/\pi r^2$, whose filling reduces the energy at the minima by an amount $E_1 = -(2\pi q^2 \sigma_1 r_c/\epsilon)$, where σ_1 is the concentration of newly captured electrons. The other states are split off in terms of the energy by an amount $q^2/\epsilon r_c$, and again a gap appears in the state density. As the states N_1 are filled, the potential minima thus descend by an amount E_1, increasing the capture rate and correspondingly reducing the band curvature. After the filling of the N_1 states, the other states are separated by a gap; i.e., the filling of these states will require a repeated curvature of the band by an amount equal to the gap width, and the process begins again. As a result, there are oscillations in the band curvature at the surface of the semiconductor, and these oscillations cause the current oscillations.

It follows that if a corresponding experiment is carried out by linearly sweeping the external gate voltage, then the oscillations in the longitudinal current should be accompanied by simultaneous oscillations in the gate charging current, due to the oscillations in the capacitance of the structure. Furthermore, the current oscillations should disappear if the system is heated or cooled to an equilibrium state at each value of the voltage. A deviation of the system from equilibrium may also be seen in the occurrence of hysteresis effects in the filling and emptying of the impurity band.

Pepper[1] observed current oscillations at electron concentrations satisfying $r_{ee} = Nx$, where r_{ee} is the average distance between electrons, x is an adjustable parameter (fixed for each sample), $N = p/4$, and p is a finite sequence of the natural numbers.

Pursuing these arguments, we can determine the electron concentration at which

the current oscillations arise. Let us assume that the charged centers for a triangular lattice and that the change in structure begins with a superperiod m times larger than the period of the lattice. After each filling the electron concentration thus increases by a fraction $1/m^2$ of the original concentration n_0, and the change in the lattice structure is completed at the concentration $3n_0$. The lattice constant becomes equal to the original value divided by $\sqrt{3}$. Oscillations thus arise at the concentrations

$$\frac{n_p}{n_0} = 1 + \frac{p}{m^2}, \tag{1}$$

where $p = 0, 1, \ldots, 2m^2$. After the structural change has been completed, we must take the new lattice as an initial lattice; when the external voltage is raised further, the filling process is repeated. We note that Eq. (1) also applies to a square lattice. In that case, p changes from 0 to m^2, and the change in the lattice structure is completed at a concentration of $2n_0$. Accordingly, the type of lattice can be determined from the positions of the current oscillations.

Table I shows the concentrations corresponding to the current maxima, as reported in Ref. 1, along with the ratios n_p/n_0 of the experimental concentrations and those calculated from (1) with $m = 2$. We take n_0 to be 1.78×10^{10} cm^{-2}. We see from this table that there are two cycles of a filling of a triangular lattice with a doubled superperiod ($m = 2$).

In what range of the concentration of charged centers can we observe the current oscillations? In the first place, the energy of the Coulomb interaction must be greater than kT if a superstructure is to be formed. Second, at values of r_{ee} greater than the thickness of the insulator, d, image forces from the metal come into play, and the Coulomb interaction between the charges drops sharply. As a result, we have the two inequalities

TABLE I.

$n_p \cdot 10^{-10}$ cm^{-2}	n_p/n_0 expt	n_p/n_0 theo	$n_p \cdot 10^{-10}$ cm^{-2}	n_p/n_0 expt	n_p/n_0 theo
1,78	1.00	1.00	5,34	1,00	1,00
2,00	1,122	–	6,10	1,128	–
2,35	1,310	1,25	6,65	1,25	1.25
2,70	1.51	1,50	8,20	1,53	1,50
3,13	1,75	1.75	9,40	1,75	1.75
3,40	1,90	–	10,60	1,98	2,00
3,54	1,98	2,00	13,50	2,53	2,50
3,90	2,18	2,25	14,90	2,79	2,75
4,30	2,41	2,50	–	–	–
4.74	2,66	2,75	–	–	–
5,34	3,00	3,00	–	–	–

$$q^2/\epsilon \cdot m r_{ee} > kT; \quad m r_{ee} < d. \tag{2}$$

For $d = 1000$ Å, the surface concentration of electrons must exceed 10^{10} cm^{-2}, while the temperature must be below 10 K, in agreement with the observations of Ref. 1.

The upper limit on the electron concentration arises because the correlation in the positions of the charged centers and the Coulomb gap disappears when the impurity band is extensively filled, so that the current oscillations also disappear.

According to (2), as the temperature is lowered there is the possibility that a superstructure with a large period (m) may form, increasing the number of current oscillations. If the temperature is instead raised, some of the oscillations may not be observed,[1,2] since the energy difference between states corresponding to adjacent values of p falls below kT.

In the case of an activation conductivity, the change in the activation energy must agree with the change in the position of the Fermi quasilevel. The difference between the activation energies at the current minimum and maximum ($\Delta\epsilon_\sigma$) thus cannot exceed the energy of the Coulomb gap, Δ. This was the situation observed in Ref. 1. The value found for $\Delta\epsilon_\sigma$ in Ref. 1 was 0.5 meV, and the value of Δ for a surface concentration of 2×10^{10} cm^{-2} was 3 meV (Ref. 5).

Pepper[1] observed that the current oscillations disappear at longitudinal fields above 10 V/cm. This result may have been a consequence of a disruption of the correlation in the field and the disappearance of the Coulomb gap.

Estimates for the experimental conditions of Ref. 1 show that the time required for the exchange of an electron between the impurity band of sulfur and the conduction band of GaAs at liquid-helium temperature is on the order of 1 s, while at 1.8 K it is on the order of 10^5 s. It is thus completely possible that the experiments in Ref. 1 were carried out away from equilibrium.

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[1]M. Pepper, J. Phys. C **12**, L617 (1979).
[2]M. Pepper and M. J. Vren, J. Phys. C **15**, L617 (1982).
[3]M. Pollak, Discuss. Faraday Soc. **50**, 13 (1970); M. L. Knotek and M. Pollak, Phys. Rev. **B9** 114 (1974).
[4]A. L. Éfros and B. I. Shklovskiĭ, J. Phys. C **8**, 49 (1975).
[5]E. V. Chenskiĭ and Yu. Ya. Tkach, Zh. Eksp. Teor. Fiz. **79**, 1809 (1980) [Sov. Phys. JETP **52**, 915 (1980)].
[6]M. S. Bello, E. I. Levin, B. I. Shklovskiĭ, and A. L. Éfros, Zh. Eksp. Teor. Fiz. **80**, 1596 (1981) [*sic*].

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