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Subbands and charge control in a two-dimensional electron gas field-effect transistor

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A calculation of the subband structure and charge distribution in an $Al_xGa_{1-x}As/GaAs$ heterojunction as a function of gate voltage at room temperature has been performed. The results show that usually about 80% of the electrons in the channel are in the lowest two subbands and describe for the first time quantitatively the transition from the simple capacitive charge control regime to the regime where the channel density is no longer controlled by the gate voltage.

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In an $Al_xGa_{1-x}As/GaAs$ heterojunction in which the AlGaAs layer is heavily doped with donors, a channel is formed in the GaAs near the heterojunction interface by electron transfer from the donors near the interface. These electrons have a high mobility because the impurity scattering has been strongly reduced by the spatial separation of the electrons and the ionized donors. If a Schottky gate is evaporated on the AlGaAs surface and the AlGaAs layer is sufficiently thin, it is possible to modulate the channel density and to construct a field-effect transistor which has properties that are very promising for high-speed logical circuits and low noise microwave amplification.[1]

Earlier models for the channel charge control have all assumed that the AlGaAs layer is completely depleted of conduction electrons and all donors are ionized. In one model[2] quantum size effects of the narrow channel are neglected, whereas another model (Ref. 3, also employed in Refs. 4, 5) in a phenomenological way takes into account the quasi-two-dimensional properties of the channel electrons. Here we shall present results of an essentially exact solution which takes into account the electronic subband structure in both the AlGaAs and GaAs layers as well as the partial neutralization of donors in the AlGaAs. The results show that generally $\sim 60\%$ of the channel electrons are in the lowest subband, so we shall keep the acronym TEGFET (two-dimensional electron gas field-effect transistor) for the device.

Our model is as follows. At $z = 0$ we have the Schottky contact with an assumed built-in barrier height of $V_{\rm BI} = 1$ eV; for $0 < z < d_2$ we have an n-doped layer of $Al_xGa_{1-x}As$ with doping concentration N_D; for $d_2 < z < d_2 + d_3$ there is an undoped AlGaAs spacer layer; and from the heterojunction interface at $d_2 + d_3$ up to the device thickness $z_0 = d_2 + d_3 + d_1$ we have the undoped GaAs grown on semi-insulating GaAs. We then perform a self-consistent calculation in which the potential for the electrons is determined by Poisson's equation and the conduction-band discontinuity ΔE_c at the AlGaAs/GaAs interface:

$$\frac{d^2V}{dz^2} = \frac{e}{\epsilon}\rho(z), \tag{1}$$

$$V(d_2+d_3-) = V(d_2+d_3+) + \Delta E_c, \tag{2}$$

where ρ is the space-charge density and $\epsilon = 13.1\epsilon_0$ is taken to be the permittivity of both AlGaAs and GaAs. The space charge is determined by the ionized impurity distribution and the distribution of free electrons:

$$\rho(z) = e[N_D^+(z) - n_{el}(z)]. \tag{3}$$

In $Al_xGa_{1-x}As$ with $x > 0.25$ the Si donor binding energies are found[6] to be rather large $E_B \cong 50$ meV, so we assume that an electron bound to a donor is well localized. Then the ionization probability of a donor is determined by Fermi statistics. For the free electrons we solve the effective mass Schrödinger equation:

$$-\frac{\hbar^2}{2m}\frac{d^2\zeta_n}{dz^2} + V(z)\zeta_n(z) = E_n\zeta_n(z), \tag{4}$$

where $\zeta_n(z)$ is the wave function and E_n is the energy of the bottom of subband n,[7] $m = 0.067m_e$ is the effective mass of electrons in GaAs and we have neglected the small difference in mass between AlGaAs and GaAs electrons. Once the subband wave functions have been determined, the free-electron density distribution is given by

$$n_{el}(z) = \sum_n |\zeta_n(z)|^2 N_n, \tag{5}$$

where $N_n = k_BTm/(\pi\hbar^2)\ln[1 + \exp((E_F - E_n)/k_BT)]$ is the occupancy of subband n and E_F is the Fermi energy which is constant throughout the system in equilibrium and set equal to 0 because the source is assumed to be grounded.

Once boundary conditions for the potential are specified, a self-consistent solution of Eqs. (1)–(5) yields the distribution of space charge and all other quantities of interest in the system. For the potential, the boundary condition at the gate at $z = 0$ is

$$V = V_{\rm BI} - eV_G, \tag{6}$$

where V_G is the applied gate voltage. The potential deep in the GaAs is slightly more complicated in principle, since it depends on the unknown unintentional doping and on properties of the undoped/semi-insulating GaAs interface. However, we have simply taken $V(z_0)$ to be a constant V_0. Apart from a rigid shift, the charge versus gate voltage characteristics do not depend on the exact value of V_0. In the results presented here, $V_0 = 1$ eV.

Table I shows the growth characteristics of the two TEGFET's for which we show results. Sample 3468 is of the normally-on type, whereas 3469 is quasinormally-off. In the calculations the number of subbands has been limited to 10;

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TABLE I. Parameters of the two devices used in the calculations.

Device nr.		3468	3469
x	Al concentration in AlGaAs	0.26	0.28
N	Doping in AlGaAs (10^{18} cm^{-3})	1.3	0.6
d_2	Doped AlGaAs thickness (Å)	550	400
d_3	Spacer thickness (Å)	75	65
d_1	GaAs thickness (μm)	1.0	0.8
ΔE_c	Conduction-band discontinuity (meV)	260	280
E_B	Donor binding energy (meV)	50	50
V_0	Potential at $d_2 + d_3 + d_1$ (eV)	1	1

in no case does the occupation of the highest subband surpass 1% of the total number of free electrons.

In Fig. 1 we show self-consistent results for the potential in the two transistors for the two gate voltages. At the lower gate voltages the AlGaAs layer is practically depleted of electrons, whereas in the second case many donors in the AlGaAs are neutralized, and a further increase of the gate voltage mainly increases the number of electrons in the AlGaAs, either as bound electrons or as conduction-band electrons, which as shown are also quantized in subbands because of the narrowness of the potential in the AlGaAs layer. As described in Refs. 8 and 9, full account has been taken of tunneling through the heterojunction barrier, but since the tunneling probability is very low electrons are practically either in the AlGaAs or in the GaAs. In the figure the subband bottom energies of the four lowest subbands are shown. It should be mentioned that the two lowest subbands contain about 50–60% and 20% respectively of the electrons in the channel except for very low densities near the threshold voltage, because the subband separation is of the order of 35 meV which is still considerably larger than $k_b T = 25$ meV. It can also be seen that for the higher gate voltages the lowest subbands are so close to the Fermi level that degenerate statistics are very important even at room temperature.

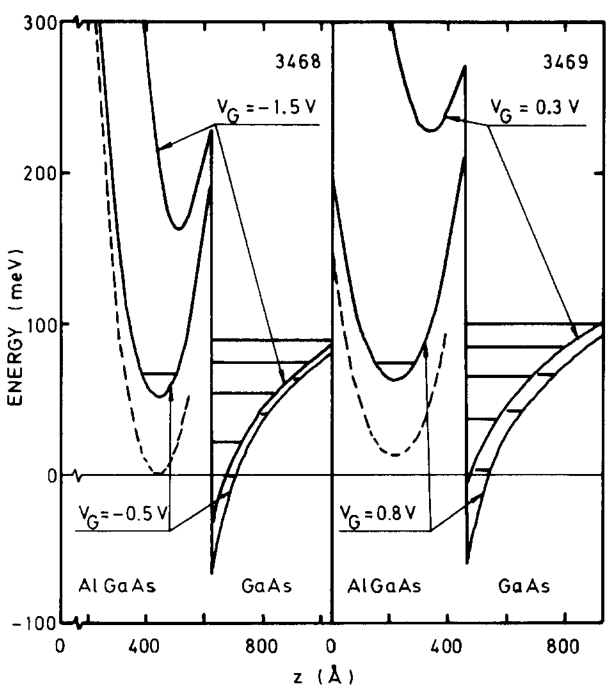

FIG. 1. Self-consistent potentials for conduction electrons in the two TEGFET's for two gate voltages V_G. Left part: normally-on device; right part: quasi-normally-off device. The Fermi level $E_F = 0$. Horizontal lines: bottom energy of the lowest four subbands. The energies of the donor levels are shown broken for the higher gate voltage.

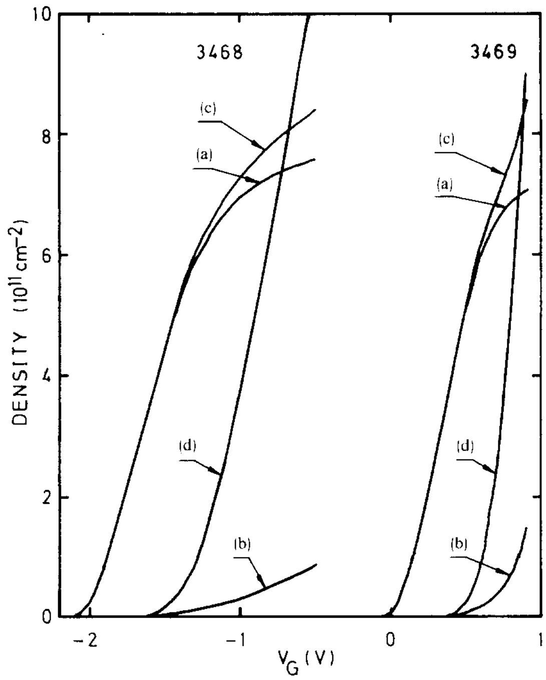

FIG. 2. Calculated electron density vs gate voltage. (a) Free electron density in GaAs channel; (b) free-electron density in AlGaAs; (c) total density of free electrons; (d) density of neutralized donors in AlGaAs.

In Fig. 2 we show the calculated density of electrons in the system as a function of gate voltage, divided into channel electrons in GaAs, bound electrons in AlGaAs, and free

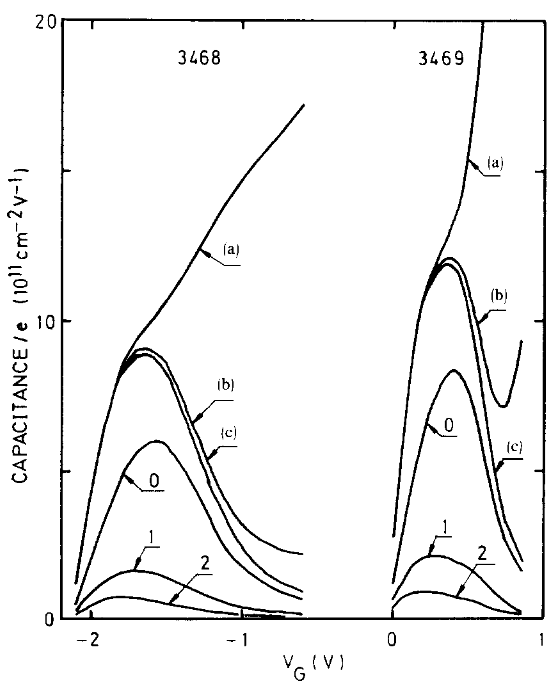

FIG. 3. Calculated capacitance edN_i/dV_G of (a) all electrons in system, (b) all free electrons, (c) all electrons in the channel in GaAs; and (0, 1, 2) electrons in lowest three channel subbands.

electrons in AlGaAs. As expected, there is an interval where the electrons induced by the gate voltage all enter the GaAs channel so that there is a fairly linear dependence of channel electron density and gate voltage as in a MOSFET. However, as the voltage increases the electrons tend to go into the AlGaAs to neutralize the donors or as free electrons, so that the density of high-mobility channel electrons saturates, which limits the useful voltage swing on the TEGFET.

A closer look at the channel electron density reveals that because of the non-negligible ratio of channel thickness to AlGaAs thickness the behavior is not linear over a very large gate voltage interval. This is different from usual MOSFET's. In Fig. 3 we show the capacitance of the channel electrons edN_{ch}/dV_G and also the derivatives of the subband occupancies for the three lowest channel subbands. It is clear from that figure that strict linearity is only obtained in a small voltage interval around the maximum in capacitance, and that the interval is broader in the normally-on device which has a thicker AlGaAs layer. Furthermore, most of the capacitance is due to the lowest subband 0.

We do not intend to discuss transport here, but in the very crudest model for the TEGFET in saturated operation one can assume that all channel electrons move with the same saturation velocity v_s. In that model transconductance and capacitance are proportional, of course, so that we see that the very high transconductance which can be obtained in the normally-off device is obtained at the cost of a large gate-source capacitance and at the cost of a very limited useful gate voltage swing, so that a high transconductance alone should not be taken as a measure of performance of a transistor.[10]

In summary, we have presented results of an essentially exact calculation of the distribution of charge as a function of gate voltage in a TEGFET with full account of the two-dimensional aspects. Our results may serve as a reference for simpler models and form a starting point for transport calculations in such devices. In particular we have been able to describe in a quantitative way the gate voltage region in which the field effect becomes limited by parallel conduction in the AlGaAs layer.

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[1]For a recent review, see N. T. Linh, in *Festkörperprobleme* (Advances in Solid State Physics), edited by P. Grosse (Vieweg, Braunschweig, 1983), Vol. XXIII, p. 227.
[2]T. Mimura, Surf. Sci. **113**, 454 (1982).
[3]D. Delagebeaudeuf and N. T. Linh, IEEE Trans. Electron Devices **ED-29**, 955 (1982).
[4]T. J. Drummond, H. Morkoç, K. Lee, and M. Shur, IEEE Electron Devices Lett. **EDL-3**, 338 (1982).
[5]T. J. Drummond, R. Fischer, S. L. Su, W. G. Lyons, and H. Morkoç, Appl. Phys. Lett. **42**, 262 (1983).
[6]T. Ishikawa, J. Saito, S. Sasa, and S. Hiyamizu, Jpn. J. Appl. Phys. **21**, L675 (1982).
[7]T. Ando, A. B. Fowler, and F. Stern, Rev. Mod. Phys. **54**, 437 (1982).
[8]B. Vinter, Solid State Commun. (1983).
[9]B. Vinter, Surf. Sci. (unpublished).
[10]S. L. Su, R. Fischer, T. J. Drummond, W. G. Lyons, R. E. Thorne, W. Kopp, and H. Morkoç, Electron. Lett. **18**, 794 (1982).