New nonlinear high-frequency effects and *S*-shaped negative differential conductivity in multilayer heterostructures

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A rapid current switching, microwave generation, and a frequency conversion of microwave radiation have been observed during vertical transport in multilayer n-GaAs-$Al_xGa_{1-x}As$ heterostructures.

In a strong electric field directed along the layers of a selectively doped multilayer heterostructure, electrons acquire energy as they overcome a potential barrier and enter a wide-gap material with a lower carrier mobility. This effect gives rise to an *N*-shaped current-voltage characteristic (a spatial analog of the Gunn effect. The ampli-

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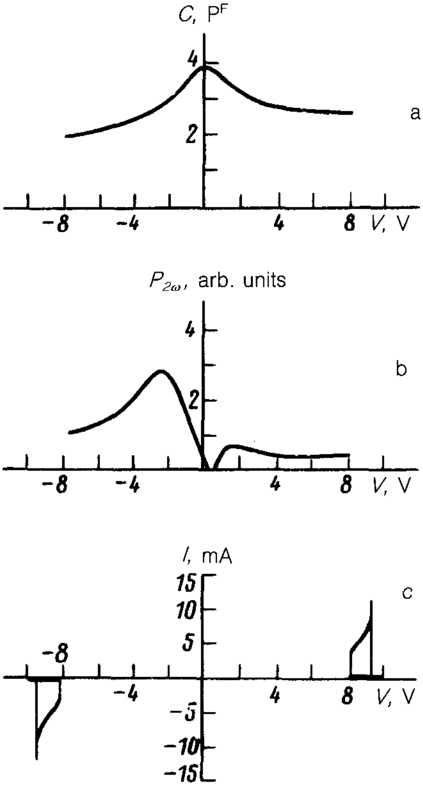

FIG. 1. (a)—Capacitance of the heterostructure versus the applied voltage; b—power in the second harmonic ($f = 150$ GHz) at a fixed power of the pump radiation ($f = 75$ GHz) versus the static voltage; c—current-voltage characteristic of a heterostructure under conditions corresponding to the generation of relaxation oscillations.

fication of oscillations associated with this mechanism has been demonstrated experimentally at frequencies up to[1] $f = 2.5$ GHz. We have now observed higher-frequency effects, specifically, a switching ($\tau < 1$ ns), microwave generation ($f > 10$ GHz), and frequency conversion ($f \approx 150$ GHz), in a selectively doped multilayer heterostructure during vertical transport (the electric field is directed perpendicular to the layers). These effects stem from the onset of an S-shaped I-V characteristic, which would naturally be linked with a rapid heating of current carriers activated into the above-barrier region when the effective barrier height is lowered by a strong electric field.

1. In the experiments we study $(n\text{-GaAs–Al}_x\text{Ga}_{1-x}\text{As})_N$ selectively doped multilayer heterostructures with a submicron period grown by (organometallic compound)-hydride epitaxy.[2] Figure 1(a) shows the I-V characteristic of a mesa diode made from a selectively doped multilayer heterostructure with a diameter $\approx 100\ \mu$m, measured at frequencies $f \approx 20$ MHz. The magnitude and characteristic voltages of the capacitance tuning correspond quite well to the representation of a redistribution by an external field of electrons in the potential wells (the n-GaAs layers), bounded by potential barriers (the $\text{Al}_x\text{Ga}_{1-x}\text{As}$ layers), in the selectively doped multilayer heterostructure. The high doping level of the n-GaAs layers and their small thickness indicate that the I-V characteristic is formed quite rapidly and that the structure has a high quality factor as a varactor element.[3] This property is demonstrated by the fre-

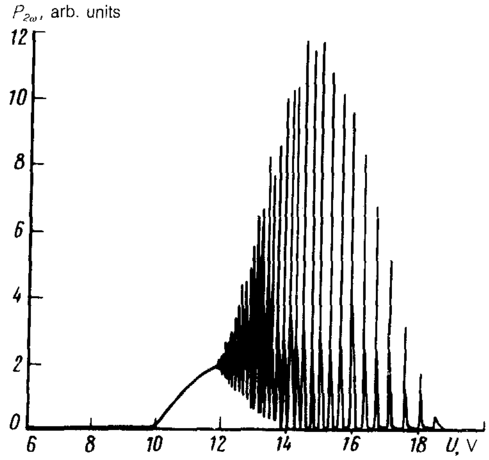

FIG. 2. Power radiated from a resonator with a heterostructure at the frequency 10 GHz versus the static voltage from the external source.

quency doubling which occurs in the range $f = 75$ GHz$\rightarrow$150 GHz in mesa diodes of smaller area. The bias dependence of the power of the signal at the doubled frequency [Fig. 2(b)] correlates well with the shape of the low-frequency *I-V* characteristic.

At voltages $V > V_s \approx 10$ V in the saturation region of the *I-V* characteristic (according to estimates, the electrons are squeezed toward one of the walls of the well under these conditions), the current is turned on with an *S*-shaped *I-V* characteristic. The turn-on voltage V_s increases in proportion to the number of periods in the samples studied. Figure 1(c) shows the current-voltage characteristic of a selectively doped multilayer heterostructure when it is operated as the active element in a degenerate relaxation oscillator powered by a dc power supply. The short length of the current pulses generated by the structure ($\tau < 1$ ns) rules out a role of heating of the lattice and indicates that the switching processes are of an electronic nature.

When the structure is connected to a microwave resonator at the frequency $f \approx 10$ GHz, we observe the generation of coherent oscillations. Figure 2 shows the microwave power generated versus the applied voltage. The oscillatory nature of this dependence may be due to the broad frequency spectrum of the oscillations that are generated and/or the rich mode structure of the distribution of the rf field in the mesa diode. The speed with which the *I-V* characteristic of the selectively doped multilayer heterostructure is established is confirmed by the frequency doubling in the range $f = 50$ GHz$\rightarrow$150 GHz. The dependence of the signal of the third harmonic that is generated on the pump power shows a threshold, which is due to the rapid turn-on of the current at an amplitude $V_\omega > V_s$ of the rf voltage.

2. In the case of vertical transport, electrons may move into the above-barrier region (in this case, into a region with a high mobility) when the effective barrier height is lowered by the electric field. At the same time, the current starts to flow (a low-resistance state). The restoration of the high-resistance state occurs at lower voltages (at a higher value of the effective barrier) because of the significant electron heating (Fig. 3). A calculation of the *I-V* characteristic in the spirit of the theory of the electron heating of compensated semiconductors with a fluctuational impurity

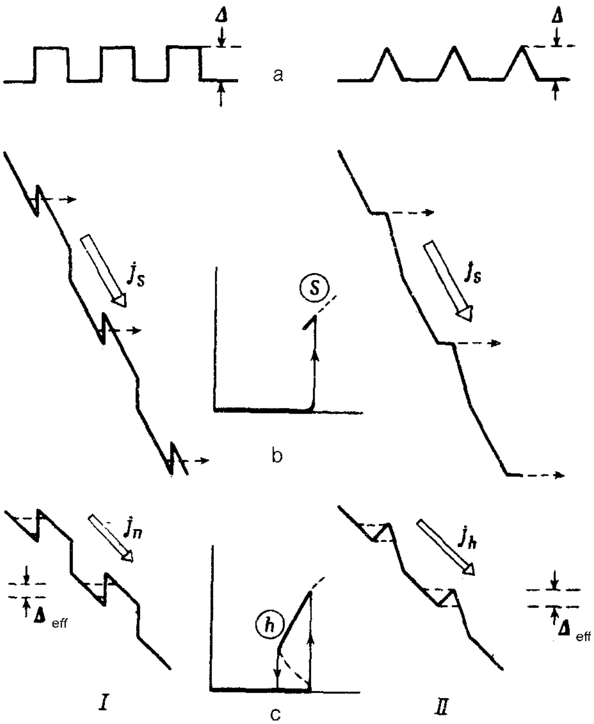

FIG. 3. Energy diagrams of a multilayer heterostructure during vertical transport. a—No applied voltage; b—turn-on state; c—current maintenance state. I) Quantum-mechanical tunneling through a vertical wall; II) "splashing" through a sloping barrier.

potential,[4] but incorporating the barrier lowering and the saturation of the drift velocity of the above-barrier electrons, yields

$$V = \frac{V_s\beta}{\beta - (j/j_s)\ln(j/j_s)}, \qquad V < V_s, \tag{1}$$

where $V_s = E_s d$ is the turn-on voltage (over one period), $j_s = qnv_s$, v_s is the saturation velocity, $\beta = 3\Delta/2l_\epsilon qE_s$, Δ is the barrier height in the absence of a field, $l_\epsilon = v_s\tau_\epsilon$, and τ_ϵ is the energy relaxation time. In the current-maintenance state (under the condition $dj/dV \to \infty$) we find

$$j_h = j_s/e, V_h = V_s e\beta/(1+e\beta), \text{ and } kT_h = \Delta/(1+e\beta).$$

The lattice temperature is $kT_0 \ll \Delta$ and has no important effect on the shape of the I-V characteristic.

For a barrier with a vertical wall, with an increase in the carrier energy due to near-surface quantization and with an increase in the tunneling transmission of the top of the barrier (the Fowler-Nordheim effect), we have $V_s = E_s d \approx 4\Delta^{3/2}m^{1/2}d/9\pi q\hbar$, and for a triangular barrier we would have $V_s \approx 4\Delta/q$ (Fig. 3). In our case both of these estimates and also the magnitude of the maintenance current ($v_s \approx 6\times 10^6$ cm/s) are close to the experimental values (Fig. 1). The time $\tau_\epsilon \lesssim 1$ ps is determined by the rapid energy relaxation among optical phonons in the presence of electron-phonon collisions.[5,6] We thus find $l_\epsilon \lesssim 500$ Å and $V_h \gtrsim 0.75V_s$, in accordance with the observed shape of the current-voltage characteristic. The short Maxwellian relaxation times of the current carriers ($\tau_M \approx 0.5$–1 ps), along with the rapid energy relaxation, indicate that the S-shaped I-V characteristic is established quite rapidly during electron heating in the selectively doped multilayer heterostructures.

The effects observed here are of interest from the standpoint of the development of ideas regarding the kinetics of hot electrons in heterostructures during vertical transport, a topic which has recently attracted considerable interest.[5,6] On the other hand, structures with a fast-response S-shaped I-V characteristic have some varied functional capabilities pertinent to applications.

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