High-gain lateral hot-electron device

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(Received 17 April 1989; accepted for publication 24 July 1989)

A lateral hot-electron device has been fabricated in a plane of a two-dimensional electron gas. The transfer ratio of the device, α, was studied for different geometrical configurations of the emitter barrier. The maximum transfer ratio was greater than 0.99 at 4.2 K, corresponding to a current gain greater than 100 for devices with base widths of 220 nm. An emission of a single longitudinal optical phonon, by the injected electrons, has been observed.

The tunneling hot-electron transfer amplifier (THETA) is a low-gain ballistic device.[1,2] Although it is a unipolar device its behavior is similar to a bipolar transistor. Because of its vertical configuration the device has some drawbacks: it is difficult to form low-resistance ohmic contacts to the narrow (~ 30 nm) base avoiding shorting of base and collector, it is difficult to expose the buried base avoiding its depletion, and it is difficult to obtain high gain because of the short ballistic mean free path (mfp) in the heavily doped base. To circumvent some of these problems we proposed and fabricated a novel hot-electron device (a "lateral THETA" device[3]) in the plane of a two-dimensional, high-mobility electron gas (2DEG). The characteristics of this lateral device are similar to those of the vertical device, but it is easier to fabricate. The device is expected to have a higher gain due to the longer mfp of hot electrons in the plane of the 2DEG. We report here on the realization of lateral hot-electron devices with a 4.2 K current transfer ratio α greater than 0.99, for base widths greater than 200 nm. We look in some detail at the injection properties of our lateral injector and also observe single phonon emission by the hot electrons.

In the vertical THETA device[4] a tunnel barrier injector emits a fairly monoenergetic hot-electron beam into the base. After their traversal through the base, the electrons surmount another thick potential barrier. This barrier prevents the equilibrium electrons that reside in the base from entering the collector. Since the collector current is only slightly affected by the shape of the collector barrier (if quantum mechanical reflections are small), the current transfer ratio is almost independent of the collector voltage and the output differential resistance can be large, as desired for device applications.

In order to make a lateral THETA device, two narrow barriers separated by a thin base were constructed in the plane of a GaAs-$Al_{0.3}Ga_{0.7}As$ selectively doped heterojunction. The 2DEG had a carrier density of $n_s \simeq 2.0 \times 10^{11}$ cm^{-2} and a mobility $\mu \simeq 7.5 \times 10^5$ cm^2/V s at 4.2 K. Utilizing nanolithography two narrow metal gates, each about 50 nm long, were deposited on the surface of the heterojunction (length is the dimension along the current path, as seen in Fig. 1). In a variety of devices the emitter gate G_E was made 0.25–1 μm wide and the collector gate G_C was made 0.75–1 μm wide, wider than the emitter gate in order to collect all of the ballistic electrons. The three regions defined by the two gates, emitter (E), base (the central region B), and collector (C) were contacted with NiAuGe alloyed ohmic contacts. An application of a sufficiently negative gate voltage, V_{GE} (or V_{GC}), with respect to the 2DEG depletes the electrons underneath the gate, forming thus a potential barrier for the electrons residing on both sides of the gate. Inducing two potential barriers, with the two gates shown in Fig. 1, enables us to reproduce, in the lateral plane, a potential distribution similar to that of the vertical hot-electron device. Using the emitter barrier as a tunnel injector produces a hot-electron distribution ~ 5 meV side.[5] Quantum mechanical reflections from the collector barrier are negligible because of the slow change of the collector barrier potential. Scattering events in the base are expected to be few due to the lower dimensionality of the base[6] and the absence of nearby impurities. Note that the tunneling currents through the wide parts of the emitter and collector gates (see Fig. 1) can be ignored, thus contacting the 2DEG in the narrow base region is established by contacting the remote, external parts of the base.

We have recently reported results of energy spectroscopy experiments made on a lateral THETA device. There we found the transport to be ballistic with ballistic distributions 3–5 meV wide.[3] In symmetric structures where the width of the emitter and the collector gates is similar, the electrons emerging from the edges of the injector, not perpendicularly

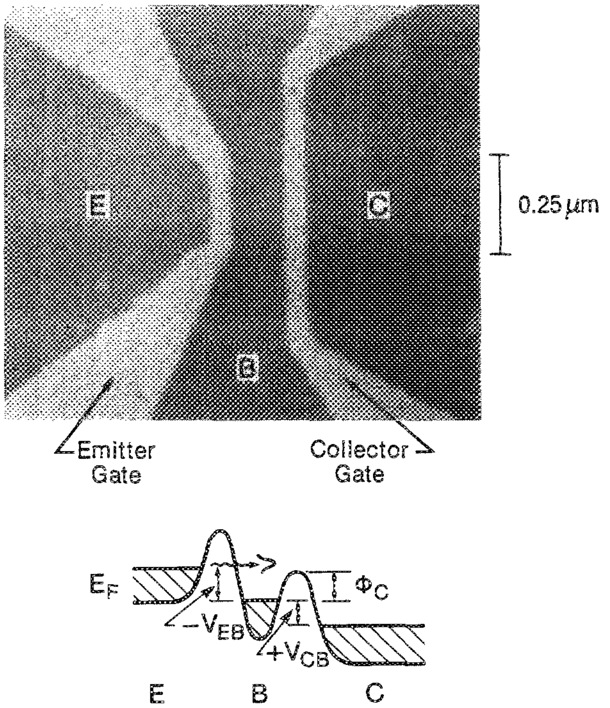

FIG. 1. Scanning electron microscopy micrograph of the lateral THETA device and a schematic description of a potential distribution for a negatively biased emitter and a positively biased collector.

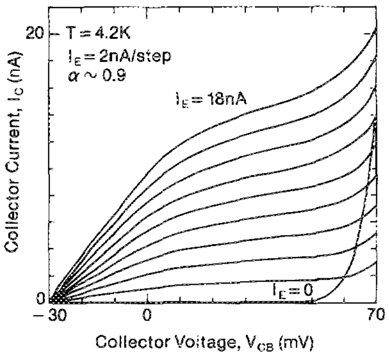

FIG. 2. Output *I-V* characteristics of the lateral device in a common base configuration. The emitter gate width is 0.25 μm, the collector gate width is 0.75 μm, and base length is 0.17 μm.

to the gates, are not collected. Indeed, in these symmetric devices, the transfer ratio $\alpha \equiv I_C/I_E$, where I_C and I_E are the collector and the emitter currents, respectively, was only 0.4 at 4.2 K.[3] To alleviate this problem a device with emitter and collector gate widths of 250 and 750 nm, respectively, and a base length of 170 nm, was made (Fig. 1). The measured output characteristics in a common base configuration are shown in Fig. 2, demonstrating a transfer ratio $\alpha = 0.9$ over a large range of injected currents and collector voltages. The ballistic fraction of the collected current, α_B, is measured at a collector to base voltage V_{CB} where the collector current I_C almost saturates ($V_{CB} \simeq 20$ mV).[3] Using $\alpha_B = \exp - d_B/\lambda = 0.7$, where d_B is the base width, we find a mfp, $\lambda \simeq 480$ nm. The true mfp is longer since some of the injected electrons emerging from the edges arrive at the collector with a low normal energy component and thus are not collected.

The solid line in Fig. 3 shows a typical dependence of α on the injection energy eV_{EB} for fixed emitter and collector barrier heights. The existence of a maximum value α_{max} is characteristic for these types of curves. In general we expect to see a monotonic increase in α due to the increasing group velocity of the ballistic electrons and the reduction of scattering cross sections as the kinetic energy of the electrons increases. Also, a larger fraction of the ballistic distribution will surmount the collector barrier.[5] The drop in α observed at higher V_{EB} is due to the relative increase of the side-tunneling current. This can be seen from the Wentzel–Kramers–Brillouin expression for the tunneling probability $D \propto \exp[-A(\phi^{3/2}w/V)]$, where A is a constant, ϕ is the emitter barrier height, w is a barrier width, and V is the applied injection voltage. From here, the ratio of the tunneling probabilities through two barriers with different widths w_1 and w_2 is $D_1(w_1)/D_2(w_2) = \exp[-A\phi^{3/2}(w_1 - w_2)/V]$, explaining the relative increase of the side currents and the drop in α beyond α_{max}. As the emitter potential barrier increases, the side currents become substantial only at higher values of injection voltages, moving thus α_{max} to higher V_{EB}'s. The increasing part of the transfer ratio curve for all emitter barrier heights, displayed in Fig. 3 (up to the maximum on the solid line) however, is not affected by the side currents.

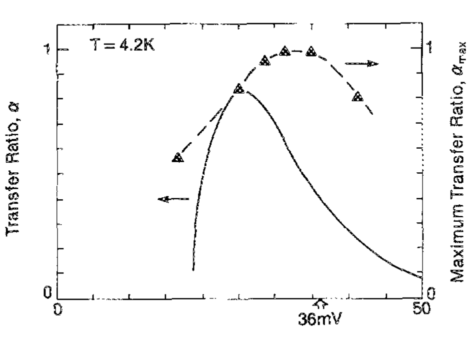

FIG. 3. Variation of the transfer ratio α with the injected voltage (a solid line) at a fixed value of the emitter gate voltage. The dashed line shows the behavior of α_{max} (extracted from a few curves of α).

Plotting the measured α_{max} for different emitter barrier heights versus V_{EB} in Fig. 3 (a dashed line) recovers the behavior of α vs V_{EB} in the absence of any side tunneling and at approximately the same injected currents. The interesting feature of the plot is the maximum reached by α_{max} (>0.98) at energies just below 36 meV. The drop in α for injection energies that exceed $\simeq 36$ meV is due to an emission of a longitudinal optical (LO) phonon (already observed in thin GaAs layers[5]). The high value of α_{max} measured here for $V_{EB} < 36$ mV suggests that LO-phonon emission is the dominant relaxation mechanism of hot electrons in a high-mobility 2DEG.

To eliminate side-tunneling currents altogether we have modified the injector structure. Two gates, each 65 nm wide separated by ~ 600 nm, were added in the emitter region as shown in the insert of Fig. 4(a). Since the emitter current is now confined to flow between these negatively biased gates (with voltage V_{GG} applied relative to base) without reaching the emitter gate corners, side-tunneling currents are prevented. Figure 4(a) shows the behavior of α for different side-gate potentials. As the negative side-gate bias increases up to -0.55 V, α increases. However, for a bias -0.6 V or greater α does not increase anymore indicating the elimination of side tunneling. A more sensitive measurement of this increase can be obtained by measuring the current gain $\beta \equiv \alpha/(1-\alpha)$, as shown in Fig. 4(b). At $V_{GG} = -0.55$ V, β exhibits pronounced maxima which move towards higher values of V_{EB} as the emitter barrier height increases. The drop in the gain for higher injection voltages is somewhat surprising since side currents have been eliminated. In a closer look we find that the gain always reaches its maximum when the injection current reaches approximately 100 nA, corresponding to a current density of $\sim 3 \times 10^3$ A cm^{-2} in the 2DEG. This is found to be the case for all emitter barrier heights and for all values of α_{max}. This observation might suggest that the decrease in the gain is related to the current density being higher than some critical value. Although this phenomenon is not yet understood, it is plausible that at a sufficiently high current density charging of the collector barrier region becomes important leading to an increase in the barrier height and to the observed reduction in the gain.

The maximum value of β is found to be as high as 105, corresponding to $\alpha > 0.99$. This is the highest current gain ever reported in a hot-electron device. The large value of the transfer ratio does not necessarily imply that the mfp is that long. At sufficiently high injection voltage the electrons are injected at energies much higher than the collector barrier

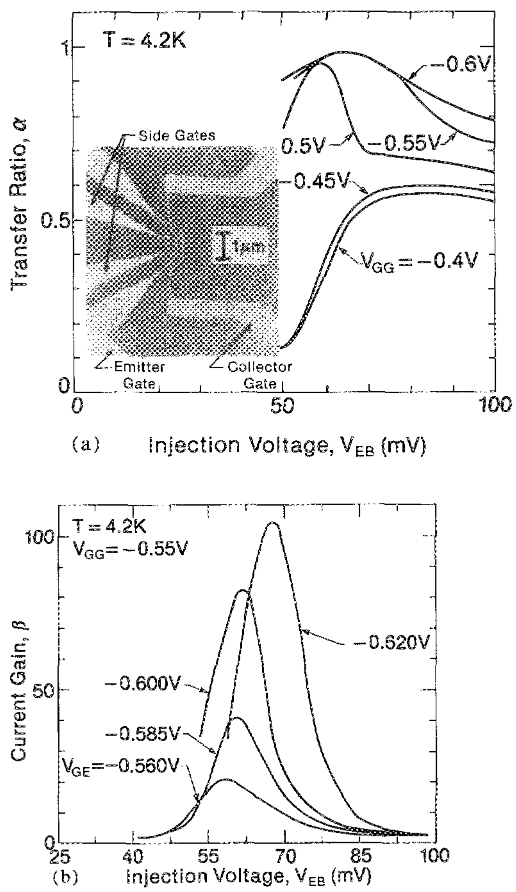

FIG. 4. (a) Effect of the side gates (inset), biased V_{GG} with respect to base, on the transfer ratio. (b) The variation of the current gain with the injection voltages V_{EB} for different emitter gate voltages in the absence of side-tunneling current.

height (which is about 20–30 meV high). Hence, they may lose a part of the normal energy component as a result of inelastic or elastic scattering and still be collected by the collector.

Our side gates can be used not only to eliminate side-tunneling currents but also to narrow the width of the emitter channel and eventually to pinch off the injector. The narrowing of the channel should result in increasing of transverse momentum components due to size quantization effects. This eventually should lead to the reduction of the current gain. We indeed observe a decrease in the gain when the channel is narrowed substantially (not shown). The maximum current gain β drops by a factor of ~ 2.5 as the side gates voltage varies from -0.55 to -0.7 V.

In conclusion, we have looked in some detail at the characteristics of a lateral hot-electron device fabricated on the plane of a high-mobility 2DEG. The high mobility of the 2DEG enabled a long mfp of the ballistic hot electrons below the LO-phonon energy. Current gains greater than 100 were measured. The possibility to tune the emitter and collector barrier heights, which are induced by submicron metallic gates, makes the device extremely powerful for studying ballistic transport and relaxation mechanisms in small systems.

We thank L. Osterling and H. Shtrikman for their contribution in the molecular beam epitaxy growth, and P. Solomon and U. Sivan for useful discussions. The work was partly supported by Defense Advanced Research Projects Agency and administered by Office of Naval Research contract No. 00014-87-C-0709.

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