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Electron interactions in the two-dimensional electron-gas base of a vertical hot-electron transistor

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We present results on the interaction of hot and cold electrons in a large-area two-dimensional electron-gas-base hot-electron transistor. Four-terminal magnetoresistance measurements of the cold electrons in the two-dimensional electron-gas (2DEG) base, as a function of forward-emitter bias, V_{EB}, show significant deviations from the zero-bias condition. We identify two distinct regimes: (i) an enhanced interface scattering as the 2DEG is forced against the collector-barrier heterojunction for low biases before emitter-current injection and (ii) an electron-heating effect in the 2DEG once current injection occurs. We invoke a simple heat-exchange argument to analyze the relaxation of the injected hot carriers.

The atomic-level precision in the control over both band gaps and doping in semiconductor multilayers afforded by molecular-beam epitaxy and metal-organic-chemical-vapor deposition has led to considerable research in the area of vertical transport in semiconductor devices.[1] Much interest has centered on the development of ultrafast unipolar-transistor structures in the $\mathrm{Al}_x\mathrm{Ga}_{1-x}$-As/GaAs and other materials systems. These exploit the possibility of hot-carrier injection into and transit across a very thin base layer (tens of nanometers thick), using suitably designed emitter and collector potential barriers.[2,3] High-speed operation of these devices requires minimal parasitic resistances and reactances, and in particular, a low base resistance which is conventionally achieved by high doping levels in the base. Under this condition, however, there is enhanced scattering of the hot injected electrons due to (a) collisions with the cold base Fermi sea and (b) the generation of the coupled plasmon-optic-phonon modes[4-6] that occur in three dimensions. This scattering degrades the energy of the injected current, reduces the fraction (α) of injected electrons collected after transiting the base, and in turn degrades the gain $[\beta=\alpha/(1-\alpha)]$ of the transistor.

One method of overcoming this problem is to modulation-dope the collector barrier so as to produce a 2DEG at the base-collector interface.[7] This may provide a relatively low-resistance contact to the base and a much-reduced scattering cross section for the injected electrons due to (i) the reduced dimensionality of the electron gas, and (ii) the perpendicular trajectory of the injected hot electrons. This follows since the 3D coupling between optic phonons and plasmons is ineffective, and the phase space for single electron-electron scattering is reduced. Simultaneous high speed and high gain should be possible. As well as these device possibilities, the two-dimensional electron-gas-base hot-electron-transistor (2DEGBHET) structure allows some interesting physics to be investigated, involving changes to the 2DEG properties with the perpendicular injection of hot electrons. A simple starting point, and the subject of this communication, is an analysis of the four-terminal Shubnikov-de Haas (SdH) oscillations of the base 2DEG as the emitter is biased.

Figures 1(a) and 1(b) show, respectively, the conduction-band profile and top view of the transistor layout for the 2DEGBHET we have been successful in realizing. The semiconductor multilayer was grown by molecular-beam epitaxy and comprised (in growth order): (i) n^+-type GaAs substrate layer, (ii) collector layer: 500 nm n-

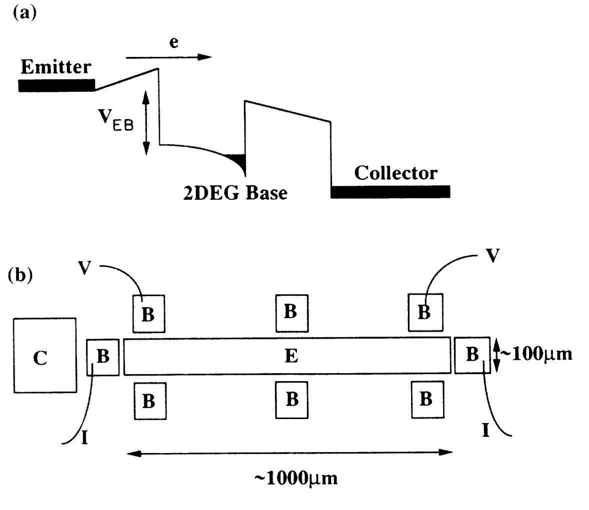

FIG. 1. (a) Schematic conduction-band profile for the two-dimensional electron-gas base hot-electron transistor, and (b) layout of the transistor structure as used in the present four-terminal measurements.

type GaAs (Si doped to 10^{18} cm^{-3}), (iii) collector barrier: 200-nm $Al_{0.3}Ga_{0.7}As$ (undoped), 15-nm $Al_{0.3}Ga_{0.7}As$ (Si doped to 10^{18} cm^{-3}), 5-nm $Al_{0.3}Ga_{0.7}As$ (undoped), (iv) base: 70-nm GaAs (undoped), (v) emitter barrier: 200-nm $Al_xGa_{1-x}As$ (x linearly graded 0.35–0, undoped), and (vi) emitter contact: 500-nm n-type GaAs (Si doped to 10^{18} cm^{-3}). Hot-electron injection occurs over the graded composition $Al_xGa_{1-x}As$ layer which forms the emitter barrier. The electrons from the modulation-doped collector barrier form a 2DEG at the base-collector interface. The multilayer was processed into a three-level mesa using a H_2SO_4:H_2O_2:H_2O wet chemical etch. The first mesa etch was terminated about 50 nm short of the base to minimize any possible surface-state problems in exposed regions of the surface that are not metallized. (An earlier attempt using plasma etching produced a poorer-quality 2DEG than that described here.) Shallow Ohmic contacts were produced using a Pd/Ge/Au metallization[8] in conjunction with a low-power electron-beam annealing schedule. A technique of repeated on-the-spot annealing and electrical probing (at both 300 and 77 K) was employed to ensure a gradual contacting to the 2DEG of the base, but without excessive penetration of the underlying collector barrier by the contact. An inevitable difficulty was met in trying to achieve a good low-temperature Ohmic contact to the 2DEG while not allowing a contact through to the collector layer. Ultimately a compromise is required, the base-base current-voltage characteristics exhibiting some Schottky-like behavior at low temperatures although the total effective series resistance is suitable low ($\sim$30 kΩ) for measurements to be taken. There may also be a contribution to the base-base resistance from surface-depletion effects, as mentioned above, but this is presumed to be small.

Curves *a* and *b* in Fig. 2 show the current-voltage characteristics of the emitter-base and collector-base barriers at 1.2 K. An emitter turn-on under forward bias and subsequent current injection at 300 mV is shown. A small fraction of this voltage is expected to be dropped vertically across the undoped base region. The collector shows a turn-on at around 150 mV under forward bias and demonstrates the existence of a suitable collector barrier, i.e., without excessive base-contact penetration. Detailed modeling of the potential profile within the device is in progress and will be reported subsequently.

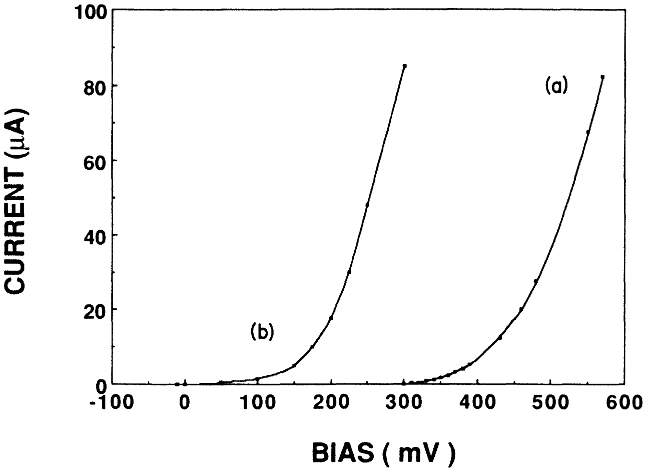

FIG. 2. (a) Emitter current vs emitter-base bias and (b) collector current vs collector-base bias.

Measurements were taken with the device biased in a common-base configuration with one base contact chosen as the common ground allowing simple transistor characteristics to be obtained from $T = 1.2$–300 K. Qualitatively similar characteristics (but with clear evidence of thermionic corrections to the currents) are found at room temperature as at low temperatures, with all contacts being Ohmic, base-base resistance of $\sim$800 Ω, a maximum base-transfer efficiency of 80% (with forward bias on the collector barrier, reducing to 60% at zero collector bias), and a common-base current gain of about four (which survives to low temperature). Throughout the experiments described here, a zero bias was maintained across the collector barrier with an appropriate collector load resistance. A standard lock-in technique enabled four-terminal low-temperature magnetoresistance measurements to be made on the 2DEG base, with a magnetic field applied normal to the 2DEG. An ac voltage source in series with a 1 MΩ resistor provided a constant ac of 1 μA between the two current contacts to the base. This current is sufficiently low to prevent electric-field heating of the 2DEG.

We note the following properties of the 2DEG in the absence of any emitter bias (see top trace in Fig. 3): from the SdH oscillation period we obtained a 2D electron density of 8.4×10^{15} m^{-2}, representing about a 55% efficiency of transfer of electrons into the 2DEG.[9] From this and the 2DEG-base resistance of $\sim$3.3 kΩ obtained from the four-terminal base-base measurement we infer a lower limit of $\sim$2.5 m^{2}V^{-1}s^{-1} for the mobility of the 2DEG. These values are comparable to those achieved in the oth-

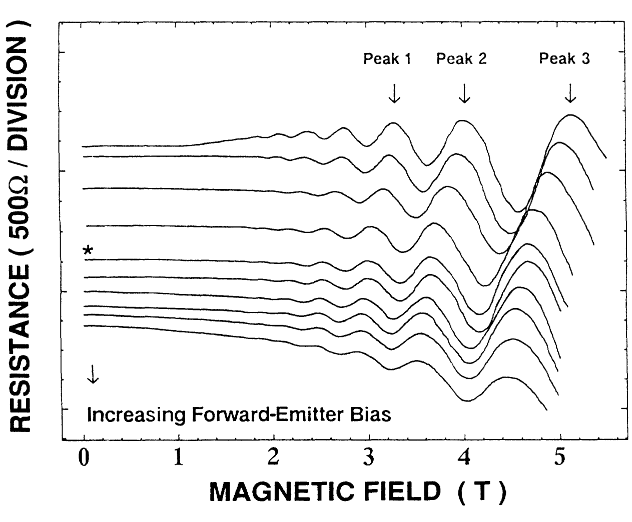

FIG. 3. Four-terminal resistance as a function of magnetic field at 1.2 K: the graphs are offset for clarity. From the top, the emitter bias values are 0, 100, 200, and 300 mV, while below the asterisk, the biases are such as to give base currents of 0.1, 1, 2, 3, 4, and 5 μA. Peaks (1), (2), and (3) are analyzed further in the text and in Fig. 4.

er back-gated and inverted heterojunction structures.[10,11]

Figure 3 shows the evolution of the Shubnikov–de Haas oscillations of the 2DEG at 1.2 K with emitter-bias V_{EB}. The oscillation amplitude decreases as the forward emitter bias is increased up to 300 mV: this can be explained by a ~15% decrease in mobility. The oscillation frequency with magnetic field also increases with increasing emitter bias: this is associated with an ~8% decrease in electron density. Both observations can be explained as a simple back-gate effect as the base region is depleted, forcing electrons closer to the base-collector interface: these results are qualitatively similar to the back-gating results of Hirakawa, Sakaki, and Yoshino.[11]

A quite different behavior occurs once the emitter injection current is turned on (see the right-hand side of Fig. 4). The SdH amplitude decreases monotonically as the emitter current increases, slowly at first and then more rapidly. The crossover regime at small emitter currents (300–380-mV emitter-base bias) will be analyzed in greater detail in a future publication. At higher emitter bias, the injection current rises rapidly leading to an almost complete suppression of the SdH amplitude, which we assume is due to a heating of the cold 2DEG by the injected hot electrons. The slight increase in periodicity of the oscillations indicates a net further reduction in carrier density of ~2.5% at 430-mV bias, a fact we use below.

An estimate of the effective electron temperature of the 2DEG as a function of base current may be obtained by considering the variation in amplitude of a given peak in the magnetoresistance oscillations. Comparison of this variation with that as a function of lattice temperature (for $V_{EB}=0$) allows an electron temperature to be extracted. Since some suppression also occurs due simply to enhanced elastic scattering, we account for this by extrapolating the low-emitter-bias data in Fig. 4, when we estimate any temperature rise of the 2DEG. Within experimental error, our analysis indicates a linear relationship between inferred 2DEG electron temperature rise (from 1.2 to ~5 K) and emitter current (up to 12 μA), over the 380–430-mV range of emitter-base bias. One possible method of hot-electron relaxation is the emission of phonons and consequent lattice heating, the latter giving rise to the observed rise in electron temperature. We can rule out this mechanism, as the joule heating energy, combined with the device size and its mounting, imply a very small temperature change ($\ll 1$ K).

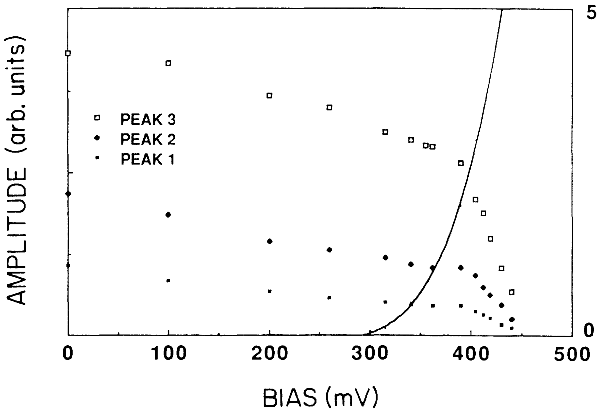

FIG. 4. Amplitude of three selected Shubnikov–de Haas oscillations as a function of the emitter-base bias voltage, with the base current superposed as a solid line.

A simple model can be introduced to describe the method by which the 40% of the injected hot electrons (at $V_{BC}=0$) lose their energy and are collected in the base. The initial process by which energy is lost is due to electron-electron interactions with the cold 2DEG. We reason as follows: using $m^* v^2/2 \sim \Delta E_C$ we obtain an injection velocity $v_{inj} \sim 10^6$ ms^{-1} and thus for a ~70-nm base width, we have a transit time of ~0.1 ps. The main alternative loss mechanism is via low-angle polar optic-phonon emission and for electron energies in undoped GaAs greater than the optic-phonon energy (~36 meV), we have a phonon emission time $t_{op} \sim 0.5$ ps.[4] We can therefore assume quasiballistic transport across the base region with respect to phonon emission and take any reduction in α from unity as being due to 2DEG interactions, possibly combined with quantum reflections at the base-collector interface.[12]

If we interpret the slowly decreasing 2DEG electron density in the heating regime as being due to a partial cancellation of a continued back-gating reduction in carrier density by those injected electrons which are trapped in the base, we can extrapolate the lower emitter-bias data to infer a net ~1% contribution to the carrier density from the trapped electrons at 430-mV emitter bias. This analysis takes into account the fact that, with injector current present, 50% of the extra bias is dropped over the contacts.

The fraction of energy that the trapped electrons lose to the 2DEG by electron-electron interaction follows from a simple heat-exchange argument involving a mixing of hot (injected electrons at effective temperature $T_{hot} = \Delta E_c/k_b \sim 3000$ K) and cold (base electrons at $T_0 = 1.2$ K) systems. We can expect an overall temperature of the 2DEG system of $\sim 3000(\Delta n_{2DEG}/n_{2DEG})$ K. The ~3–4-K temperature rise obtained above implies $\Delta n_{2DEG}/n_{2DEG} \sim 0.1\%$, if all the heat were lost to the 2DEG. The interpretation of the data given above suggests that energy losses to phonons must be ~10 times more effective than to the base electrons, the exact factor depending on the accuracy of the two estimates of Δn_{2DEG}.

Since $\Delta n_{2DEG} = I_B/wev_d$ (with w the base width) we would require $v_d \sim 2500$ ms^{-1} for our model to explain the data. The actual velocity distribution of those injected electrons trapped in the base as they scatter from high- to low-energy states during lateral transit to the base contact is a complex problem, needing further detailed theoretical analysis. We can start by extracting what is an entirely reasonable *energy* relaxation half-length of ~0.5 μm by assuming an exponential fall of the in-plane velocity with distance along the base after an initial scattering. We extract this characteristic length by equating the average velocity of the injected electrons over the typical center-emitter to center-base distance of 500 μm to the value required to give the ~1% increase in base electron density implied from the magnetoresistance data. This half-length corresponds to an optic-phonon-emission distance of order 0.15 μm, somewhat greater than the 0.03–0.04 μm values achieved when electrons are injected into a doped base transistor, as restricted phase-space arguments would predict, but less than the value for undoped GaAs.[4] Note that if we were to assume a very rapid energy relaxation of the injected carriers, the estimated bias within the base would imply a very small drift velocity, and in turn a $\sim 50\%\ \Delta n_{\mathrm{2DEG}}$, which is not observed.

In this Rapid Communication, we have presented the first studies of the cooling of very hot electrons injected into a cold two-dimensional electron gas. The precise mechanisms by which hot electrons lose their energy in the base, and interact with the 2DEG, deserve more attention. Our simple model is an important first step along the way. Subsequent experiment work will examine the effect of electron heating and relaxation on the quantum Hall effect. In addition, a transverse magnetic field can be used to deflect the injected current thus allowing us to study these interactions as a function of incidence angle of the injected electrons upon the 2DEG.[13]

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