Direct injection tunnel spectroscopy of a *p-n* junction

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We demonstrate spectroscopic measurements on an InGaAs *p-n* junction using direct tunnel injection of electrons. In contrast to the metal-base transistor design of conventional ballistic electron emission spectroscopy (BEES), the base layer of our device is comprised of a thin, heavily doped *p*-type region. By tunneling directly into the semiconductor, we observe a significant increase in collector current compared to conventional BEES measurements. This could enable the study of systems and processes that have thus far been difficult to probe with the low-electron collection efficiency of conventional BEES, such as luminescence from single-buried quantum dots. © 2009 American Institute of Physics. [DOI: 10.1063/1.3177191]

Ballistic electron emission spectroscopy (BEES) has been shown to be a useful probe of electron transport through buried metal-semiconductor interfaces,[1,2] semiconductor heterojunctions,[3] and quantum dot structures.[4] Its optical counterpart, ballistic electron emission luminescence (BEEL), has enabled the study of luminescence from buried structures,[5,6] but thus far the spectroscopic study of luminescence from a single-buried structure such as a quantum dot has remained elusive. The primary obstacle to such an experiment is the low collector current attainable in conventional BEES/BEEL techniques, which typically utilize a thin-metal layer for the base electrode.[7,8] Electrons tunnel into the base metal, and, except in select systems such as epitaxial Bi on Si,[9] the vast majority (>99.9%) are unable to traverse it and enter the semiconductor before they scatter and thermalize to the chemical potential of the base layer. For systems with an optically active collector made of a III-V material such as GaAs, even epitaxial base layers have shown significant scattering.[10]

Here we report spectroscopic results from a structure, shown in Fig. 1(b), in which the base electrode is instead formed by a thin, heavily doped surface region of the opposite polarity from the semiconductor collector.[11] By replacing the metal base layer with a thin layer of *p*-type semiconductor, several electron-scattering processes, detailed in Ref. 12, are eliminated. The first is scattering while traversing the base layer, the probability of which is given by $P_\lambda = \exp[-d/\lambda]$, where d is the thickness of the metal-base region and λ is the inelastic mean-free path.[13] For a typical 10 to 20-nm-thick base layer of Ag, Au,[13] or ErAs,[14] $P_\lambda \sim 0.1$. In addition, in metal-base or InAs-base systems,[15] the large potential step at the base-collector interface has a high probability of reflection, $P_{QM} \sim 0.75$.[16] In our system, in contrast, the potential energy varies smoothly between the base and collector layers, resulting in a significantly lower probability of reflection. Finally, in metal-base systems such as Au/GaAs, the probability of traversing the metal/semiconductor interface without scattering, P_{BC}, has been experimentally shown to be ~ 0.1.[17] In our device, the base and collector are made of the same material, so this scattering mechanism is

not present. Thus we would expect that for the same emitter structure and tunnel barrier, the collector current of a direct-injection device could be larger than that of a metal-base device by roughly $[P_\lambda P_{BC}(1-P_{QM})]^{-1} \sim 400$.

Parasitic effects in the direct-injection device may slightly reduce this estimate, but such effects should be negligible in an optimized structure. Minority-carrier recombination within the *p*-type region is negligible for such a thin layer, as has been shown in bipolar transistors.[18] Additionally, surface recombination at the oxide-semiconductor interface should be insignificant because the emitter electric field will accelerate electrons away from the semiconductor surface.

The device used in this experiment was grown by molecular-beam epitaxy, lattice matched on a (100) *n*-type doped InP substrate. In order from surface to substrate (base to collector), the layers were: 50 nm $In_{0.53}Ga_{0.47}As$ (*p*-type doped 1×10^{19} cm^{-3} with Be); 300 nm $In_{0.53}Ga_{0.47}As$; and 500 nm $In_{0.53}Ga_{0.47}As$ (*n*-type doped 3×10^{18} cm^{-3} with Si). Devices were fabricated by etching circular mesas of
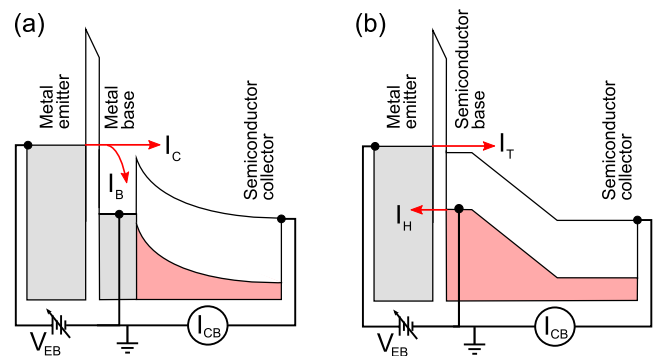

FIG. 1. (Color online) (a) Schematic energy-band diagram of a conventional, metal-base device under conditions of negative V_{EB}. Of the tunneling electrons, only a small fraction I_C enter the collector; the vast majority scatter and lose energy within the base metal, forming I_B. (b) Schematic energy-band diagram of a direct tunnel injection device shown under similar bias conditions. Because the base electrode is formed by a doped-semiconductor layer, there is less attenuation of the tunnel current, and I_C can be orders of magnitude higher than in a metal-base device. The transfer ratio is ultimately limited by hole tunneling from the base into the emitter (I_H).

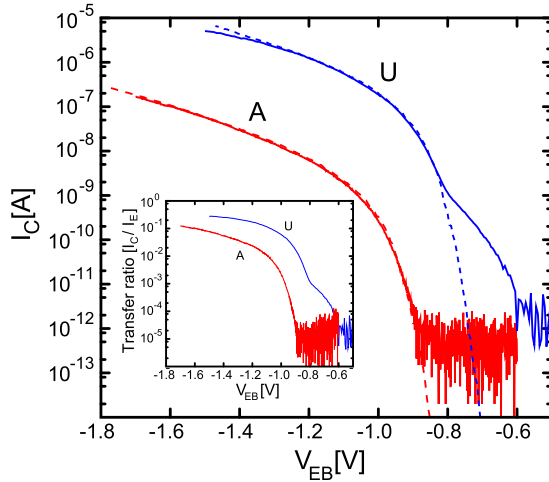a)Electronic mail: krussell@post.harvard.edu.

FIG. 2. (Color online) Collector current of an unannealed device (U) and a different, annealed device (A) as a function of emitter-base bias. Solid lines are measured data; dashed lines are simulation results for a 2.2 eV barrier of thickness 1.76 nm (U) and 2.08 nm (A). Simulations have been shifted in bias by less than 100 mV for better agreement, as described in the text. Both samples show a sharp turn-on near $V_{EB}=-0.8$ V (corresponding to the expected conduction band edge of InGaAs) and generally agree with the simulation. (Inset) Transfer ratios (I_C/I_E) for the two devices. Both achieve values greater than 10%.
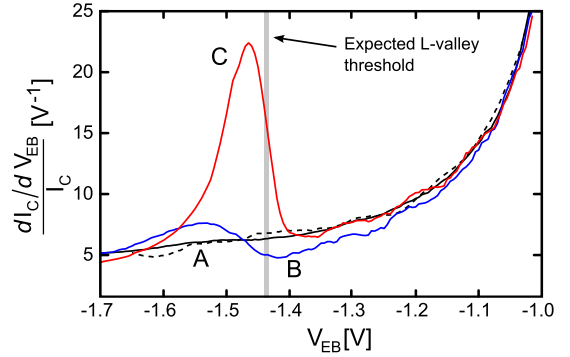

FIG. 3. (Color online) Logarithmic derivative of measured collector current (dashed line) from the annealed sample of Fig. 2, as well as various simulations (solid lines, labeled). (A) Simulation with a 2.08-nm-thick barrier (the same simulation as shown in Fig. 2). No feature is visible at the L-valley threshold near -1.45 V. (B) Simulation of a thinner tunnel barrier (0.80 nm); here the L-valley threshold is apparent. (C) Simulation with 2.08-nm-thick barrier with no $k_\parallel$-conservation. The peak is from L-valley density of states.

150 μm diameter and $\sim$500 nm height. Al_2O_3 tunnel barriers were formed by fully oxidizing a thin ($\sim$1 nm) sputtered Al film using a UV$-O_3$ treatment for 10 min at 100 °C. Emitter electrodes of $\sim$20 nm Al or Al\Ti\Au (10\10\10 nm) were sputtered on top of the oxide. Sputtered Ti\Au (10\50 nm) contacts were made to the emitter, base, and collector for electrical access to each of the layers. The resistance of the base layer was not separately measured but was expected to be negligible because the p-type base-layer conductivity increases with negative V_{EB} in the area underneath the emitter electrode, as in a p-channel FET.[18] All measurements were made at 77 K in a common-base configuration.

Shown in Fig. 2 are traces of collector current I_C versus emitter-base bias V_{EB} from two devices: one measured prior (U) and the other subsequent (A) to annealing for 1 min at 300 °C in Ar. Similar annealing treatments have been shown to increase the resistivity, stability, and break-down field of Al_2O_3 tunnel barriers.[19] As in a conventional BEES device, we expect the collector current I_C to be negligible unless the tunneling electrons have sufficient energy to enter the collector. In our device, the chemical potential μ_B of the p-type base is approximately equal to the energy of the valence band E_{VB}, so the threshold in I_C occurs when qV_{EB} is approximately equal to the band gap of the semiconductor ($\sim$0.8 eV at 77 K).[20] In some devices, such as the unannealed device shown in Fig. 2, we observed an additional threshold near $V_{EB}=-0.6$ V whose origin is unknown but presumably related to defects or In nonuniformity within the base layer.

Also shown in Fig. 2 are Monte Carlo simulations of I_C calculated following the general format of Ref. 17:

$$I_C = eA\frac{\hbar}{m}\frac{n}{2N}\sum k_\perp P_{occ}(E)P_{vac}(E)$$

$$\times P_{DOS}(k_\parallel,k_\perp)P_{tunnel}(k_\perp), \quad (1)$$

where e is the electron charge; A is the device area; m is the

electron effective mass; n is the emitter electron density; N is the sampling number (10^8); $\hbar k_\perp$ is the momentum in the direction of tunneling (perpendicular to the surface); $P_{occ}(E)$ is the occupation probability of a state with energy E in the emitter; $P_{vac}(E)$ is the probability of vacancy of a state of energy E in the collector; $P_{DOS}(k_\parallel,k_\perp)$ is the probability that a state with momentum components $\hbar k_\parallel$ and $\hbar k_\perp$ parallel and perpendicular to the layers, respectively, exists in the semiconductor; and $P_{tunnel}(k_\perp)$ is the tunneling probability calculated using the scattering-matrix formalism.[21]

To achieve agreement with experimental data, we varied three simulation parameters: tunnel barrier height, tunnel barrier thickness, and μ_B (relative to the semiconductor valence band). For both the annealed and unannealed devices, we obtained best agreement with a 2.2 eV barrier height. The resulting value for the thickness of the annealed barrier (2.08 nm) was slightly larger than that of the unannealed barrier (1.76 nm), consistent with the reported effects of annealing.[19] As expected, μ_B was found to be within 100 meV of E_{VB}: $\mu_B=E_{VB}+25$ meV for the unannealed device and $\mu_B=E_{VB}-90$ meV for the annealed device. A drawback to the direct injection approach is that μ_B is a sensitive function of surface Fermi-level pinning and base doping and thus could be altered by annealing. However, we did not measure a sufficient number of devices to enable a systematic study of the effects of annealing on μ_B.

As in conventional BEES, the collection probability in our structure can vary significantly depending on whether $k_\parallel$ is conserved during transport. This becomes especially apparent for qV_{EB} near the threshold of the conduction band minimum at L ($\sim$550 meV above the threshold of Γ)[20] in $In_{0.53}Ga_{0.47}As$. The valley at L has a large density of states, but those states are located at {111} and therefore have large projected $k_\parallel$ in the (100) plane of the semiconductor surface. Because the tunneling probability depends exponentially on $k_\perp$, if $k_\parallel$ is conserved, then $k_\perp$ must be reduced according to $k_\perp^2=2mE/\hbar^2-k_\parallel^2$, and the current entering L will be exponentially suppressed.

In conventional BEES, however, it is common for $k_\parallel$ conservation to be disrupted by scattering.[10,16] In such cases, the large density of states at L leads to an increase in I_C at the threshold of L that is visible in derivative spectra. In Fig. 3,

we investigate this regime using the logarithmic derivative of I_C. In contrast to conventional BEES measurements, the measured I_C in our device agrees with the simulation of $k_\parallel$-conserved transport (line A). The simulation with identical sample parameters but without $k_\parallel$ conservation (line C) is clearly not a good description of transport in our device. Shown for comparison is a $k_\parallel$-conserved simulation with a thinner tunnel barrier (line B), in which the threshold at L is visible. Simulations of various barrier thicknesses (not shown) indicate that the threshold at L is visible in $k_\parallel$-conserved systems only for junctions thinner than ~ 1.2 nm. We cannot fabricate and measure a device with such a thin Al_2O_3 barrier because the voltage needed to reach the threshold at L would cause the emitter-base electric field to exceed the breakdown field of the barrier.[19] However, using the tip of a scanning tunneling microscope as an emitter electrode could allow probing at a variety of barrier thicknesses, and we are planning to perform such measurements in the future.

In summary, we have demonstrated spectroscopic measurements of direct tunnel injection into a *p-n* junction. The observed I_C versus V_{EB} agrees very well with simulations that include $k_\parallel$ conservation. Because this approach can provide higher I_C than conventional BEES/BEEL, it represents a significant advance towards the spectroscopic study of luminescence from single buried quantum structures.

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