Ballistic hole emission luminescence

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Using a method complementary to ballistic electron emission luminescence (BEEL), we demonstrate tunnel-junction injection of sub-band-gap hot *holes* into the valence band of a semiconductor heterostructure to generate band-gap luminescence. This mechanism can be used in a scanning-probe geometry for the development of a simultaneous hole transport and luminescence microscopy of *p*-type Schottky devices. © *2004 American Institute of Physics*.
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Ballistic electron emission luminescence (BEEL) utilizes tunnel-junction injection of hot electrons ballistically through a metal base and into a specifically designed *p-i-n* heterostructure collector for subsequent band-gap luminescence. This technique has been used in the solid state for light-emitting metal base transistors,[1] luminescent spin-valve transistors,[2] and with a scanning tunneling probe in the development of a sophisticated hot-electron microscopy.[3,4]

In BEEL, electrons tunnel across the insulating tunnel barrier (whether it be an oxide or vacuum) to convert potential energy from a negative electrical voltage bias applied to the emitter into kinetic energy in the base, as in Fig. 1(a). If this energy exceeds the Schottky barrier (SB) at the metal-semiconductor interface below the tunnel point, and the base is thin enough for ballistic (no scattering) transport, a significant fraction of the tunneling electrons can be injected into the *p-i-n* semiconductor collector. Although Fig. 1(a) shows an unbiased collector, to allow the injected electrons to find holes from the *p*-type layer for radiative recombination, a positive voltage bias must be applied to the collector, pulling the conduction band down and canceling the built-in field between the *n*- and *p*-type layers.

It may seem trivial to reverse both the doping profiles in the design of the collector heterostructure and the polarity of operating voltages to repeat this process using hole injection. However, this type of mirror charge complementarity is important for applications where one type of carrier injection is deemed more desirable. This could be either for device operation reasons or because material restrictions do not permit *n*-type layers grown on top of heavily doped *p*-type layers due to dopant diffusion and subsequent defect formation. In this letter, we report on a ballistic hole emission luminescence (BHEL) device based on AlGaAs/GaAs, completely complementary to previously published BEEL devices.

Our heterostructure device was grown via molecular beam epitaxy with the following structure: heavily doped *n*-type GaAs substrate, 300 nm *n*-type GaAs buffer layer doped to 5×10^{18} cm^{-3}, 300 nm *n*-type $Al_{0.30}Ga_{0.70}As$ doped to 5×10^{18} cm^{-3}, 10 nm GaAs undoped quantum well (QW), 100 nm *p*-type $Al_{0.30}Ga_{0.70}As$ doped to 2×10^{17} cm^{-3}, and a 20 nm *p*-type GaAs cap layer doped to 2×10^{17} cm^{-3}. All *n*-type doping is with Si, all *p*-type doping is with Be. A schematic band diagram of the unbiased collector heterostructure, with surface tunnel-junction hole emitter, is shown in Fig. 1(b).

Although the band-diagram of the BHEL collector is nearly the inverse of the BEEL band diagram, there is one important difference between BEEL and BHEL devices: tunnel-junction carrier emission energy distribution. Electrons have a higher probability of tunneling from emitter to base through a barrier as their energy is increased; in BEEL, this results in an emitted electron energy distribution peaked near the emitter Fermi energy. Hot electron injection into the semiconductor collector is then relatively likely if this energy exceeds the SB between the base metal Fermi energy and the semiconductor collector conduction band. When the dopant type and tunnel junction bias is reversed in a BHEL device, electrons now tunnel from base to emitter, and the peak in energy distribution is near the Fermi energy of the base, close to the middle of the band gap. Hot holes left behind by tunneling electrons have an identical (not inverted) energy

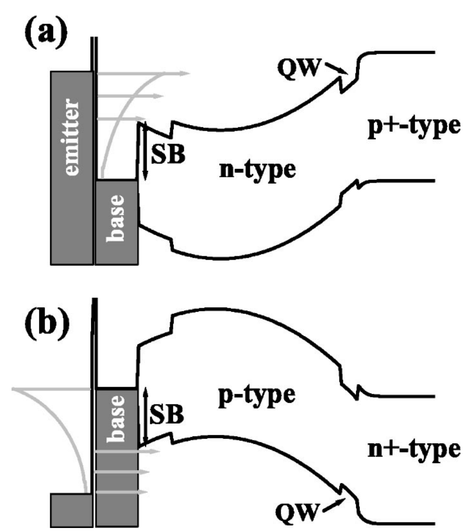

FIG. 1. Schematic band diagram for a BEEL device, (a), and for a BHEL device, (b). The emitter is shown biased, and the collector unbiased in both. In BEEL, the energy distribution of emitted electrons favors Schottky-barrier hot electron collection; this distribution makes hot hole injection in BHEL more difficult.

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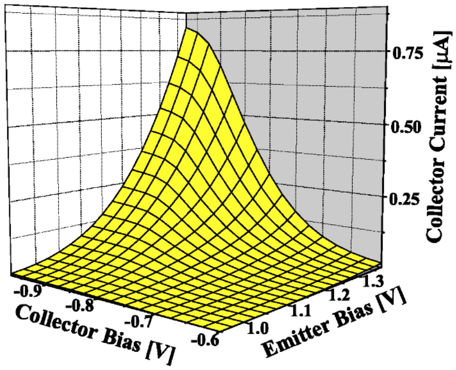

FIG. 2. Injected hot hole collector current as a function of the emitter and collector voltage biases for the ballistic Hole Emission luminescence device at 77 K.

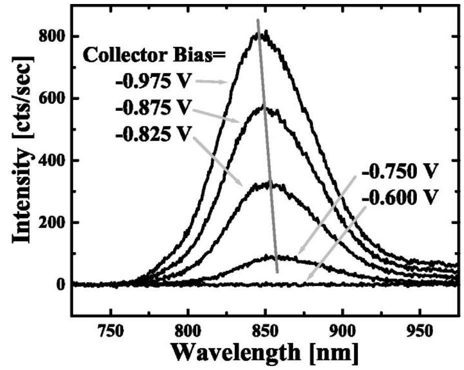

FIG. 3. Ballistic hole emission luminescence at constant emitter bias (1.375 V), for several collector biases at 77 K. The gray line indicates the blueshift caused by the $V_{collector}$-induced quantum-confined Stark effect.

distribution, peaked far away from the valence band edge. This means that injected holes must now originate from the exponentially attenuated *tail* of the energy distribution, not the peak (as in BEEL), resulting in a low emitter to collector current ratio. In order to get significant collector currents in BHEL devices, the tunnel-junction resistance must therefore be low to give high emitter currents. This design concept was incorporated into the critical fabrication step of tunnel-junction formation.

The wafer was processed using standard shadow-mask and photolithographic techniques. After cleaning the surface with dilute NH_4OH, 80 Å of Al was deposited via thermal evaporation at high vacuum to form a 500×500 μm^2 base Schottky contact. The specific thickness of this Schottky contact was chosen to minimize ballistic hole and emitted photon attenuation while ensuring a continuous film. Next, 1000 Å of Al_2O_3 was deposited via electron-beam evaporation over a portion of the Al to form an insulating region. Unlike previous studies where tunnel junctions were used for electron emission,[1,2,5] UV ozone oxidation was not applied. Two $\approx 400\times 100$ μm^2 structures of 450 Å Al were deposited via thermal evaporation to form emitter and base contacts, partially on the Al_2O_3 insulator for bonding without any intentional oxidation of the base layer. This was to ensure a thinner oxide tunnel barrier and consequently less resistive tunnel junctions. The sample was then processed into device mesas 2 μm high and of area $\approx 700\times 700$ μm^2 by patterning with photolithography and etching with $NH_4OH/H_2O_2/H_2O$ 1:1:5 for 60 s.

Electrical contact to the collector substrate was made by cold pressing an In contact to the back surface. All measurements were performed using an optical cryostat at 77 K to reduce thermionic collector leakage below the measurement sensitivity (10 pA). The luminescence was collected with a 0.2 NA lens, and the spectra were recorded with a Thermo-Oriel MS257 spectrograph with a cooled charge-coupled device (CCD) camera and a diffraction grating with 150 lines/mm and a blaze wavelength of 800 nm.

Hot holes were injected into the collector valence band at the Schottky interface by positively biasing the emitter with respect to the base via an emitter voltage ($V_{emitter}$). Electrons were injected into the conduction band through the ohmic substrate contact by negatively biasing the collector via a collector voltage ($V_{collector}$).

Figure 2 shows a surface plot of the collector current as a function of the two independent parameters ($V_{emitter}$ and $V_{collector}$) over the range $-0.975 < V_{collector} < -0.6$ V and $0.95 < V_{emitter} < 1.375$ V, with 25 mV resolution. As discussed previously, the tunnel-junction resistance was chosen during fabrication to be very low to increase the injected collector current. At $V_{emitter}=0.95$ and 1.375 V, the emitter current $I_{emitter}=5$ and 8 mA, respectively. In this case, the resistance of the thin base film (≈ 100 Ω) is not negligible, so a small but significant fraction of the emitter bias drops across it. This means that the SB, usually indicated by the threshold in $V_{emitter}$ spectra (for instance, at $V_{collector}=-0.975$ V), is actually lower than the ≈ 1 V indicated.

At constant $V_{emitter} >$ SB, the collector current increases only when $V_{collector}$ exceeds the voltage necessary to null the built-in field between the *n*- and *p*-type AlGaAs layers, allowing injected holes to reach the QW. This criteria is satisfied at approximately -0.8 V. However, the base voltage drop (which increases the apparent SB threshold in $V_{emitter}$ spectroscopy) adds to the effective collector voltage bias, lowering the measured $V_{collector}$ threshold. The actual intrinsic value for the built-in voltage drop between the *n*- and *p*-type layers is expected to be higher than 0.8 eV.

Figure 3 shows typical spectra of emitted luminescence caused by hot hole injection for various values of $V_{collector}$ at a constant $V_{emitter}=1.375$ V. The photon energy evident from the figure (≈ 1.46 eV) offers another, simpler, explanation for the collector bias threshold, which does not invoke a band diagram:[6] Hot holes supply energy equal to the SB, so a collector bias corresponding to *at least* the energy of the QW band gap minus the SB height is necessary to induce band-gap photon emission. Although the emission wave-

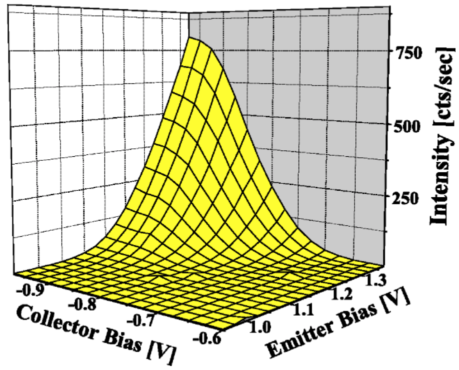

FIG. 4. Ballistic hole emission luminescence peak heights measured simultaneously with the data presented in Fig. 2. A collector bias threshold similar to the threshold seen in BEEL (Ref. 1) is evident.

length is higher than expected for quantum-well luminescence, the slight blueshift in peak position with increasing $V_{collector}$ (characteristic of the quantum-confined Stark effect) indicates that the photons originate from the GaAs QW layer.[7]

In Fig. 4, we present the magnitude of the band-gap luminescence which was collected simultaneously with the collector current data shown in Fig. 2. The two surface plots share the same $V_{emitter}$ and $V_{collector}$ dependence, further indicating that the luminescence is a result of the injected hot hole current.

In conclusion, we have demonstrated a luminescent hot hole tunnel-junction transistor which operates complementary to BEEL. This device may enable design of an alternative class of light-emitting devices and add to the development of BEEL-type scanning microscopy for materials in which the simultaneous study of local hole transport and radiative emission are of interest or where restrictions exist on the doping layer sequence.

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