

Ballistic electron emission luminescence spectroscopy of an InAs quantum dot heterostructure

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We present ballistic electron emission luminescence (BEEL) spectroscopy measurements of an InAs quantum dot (QD) heterostructure based on three-terminal hot electron injection using a scanning tunneling microscope (STM) and a planar tunnel-junction transistor. Due to higher injected current, the planar transistors allow us to perform wavelength spectroscopy of the emitted luminescence, which resolves both quantum-confined Stark-shifted QD luminescence near 1.34 eV and bulk GaAs luminescence at 1.48 eV. This facilitates interpretation of STM BEEL spectra as a function of collector voltage bias. By freezing out the collector leakage current at low temperatures, consistent collector-current spectra are acquired with both STM and planar transistors. © 2004 American Institute of Physics. [DOI: 10.1063/1.1790595]

As a three-terminal modification of a scanning tunneling microscope (STM) in a hot electron transistor configuration, ballistic electron emission microscopy (BEEM) and its associated spectroscopy (BEES) have been widely used to study metal-semiconductor interfaces and buried semiconductor heterostructures.^{1,2} In contrast to a hot electron transistor, BEEM utilizes a scanning tip and vacuum gap instead of a planar solid-state tunnel junction (TJ) to inject hot electrons ballistically through the metal base layer into the semiconductor collector with a rectifying Schottky barrier (SB) at the metal-semiconductor interface as an energy filter. The collector current is a sensitive probe of the local SB height, or band offset of buried heterostructures, provided that their depths are within the electron ballistic mean free path.

Recently, a combination of BEEM and BEES with luminescence technique, i.e., ballistic electron emission luminescence (BEEL), has been developed to study the current transport and light-emission properties of direct-gap semiconductor heterostructures simultaneously.³⁻⁵ Unlike BEEM and BEES measurements, where a unipolar *n*-type semiconductor Schottky diode is used, BEEL requires the combination of an *n*-type Schottky interface with a *p-i-n* light-emitting-diode-like heterostructure in the same device. By applying an emitter voltage higher than the SB height, electrons are injected into the *n*-type surface layer of the semiconductor collector as majority carriers, which have long lifetimes to recombine radiatively with holes in a buried optically active layer and emit interband luminescence. As required by energy conservation, a collector voltage bias larger than the energy difference between the emitted photon and the SB height is needed to induce luminescence.⁶ Compared with scanning tunneling luminescence (STL),⁷ which collects photons emitted from the sample surface as the result of inelastic tunneling,⁸ impact ionization or minority carrier injection,⁹ BEEL studies interband luminescence of semiconductor heterostructures buried much deeper than the limit of electron ballistic mean free path.

Here we report on BEEL spectroscopy measurements of an InAs quantum dot (QD) heterostructure. This material is chosen as our model system partly because of its importance for electro-optical applications, such as semiconductor lasers.¹⁰ It also provides us an opportunity to test the feasibility of BEEL as a spectroscopic technique to study the current transport and spontaneous emission properties of quantum-confined heterostructures. The design principle applied to the InAs QD heterostructure is similar to what has been reported before,³⁻⁶ except that the GaAs quantum well layer in those works is now replaced by a layer of InAs self-assembled QDs as the active light-emitting region.

The QD heterostructure is grown via molecular beam epitaxy on a (100) *p*⁺-GaAs substrate with the following structure (in the order of substrate to surface): 300 nm *p*-GaAs buffer layer doped to $5 \times 10^{18} \text{cm}^{-3}$, 2 nm undoped GaAs spacer, a layer of undoped InAs QDs,¹¹ 5 nm undoped GaAs spacer layer, 4 nm *n*-GaAs doped to $2 \times 10^{17} \text{cm}^{-3}$, 91 nm *n*-Al_{0.3}Ga_{0.7}As doped to $2 \times 10^{17} \text{cm}^{-3}$, and a 20 nm *n*-GaAs cap layer doped to $2 \times 10^{17} \text{cm}^{-3}$. In all epitaxial growths, Si is used as the *n*-type dopant and Be is used as the *p*-type dopant. The substrate dopant is Zn.

Due to the much larger active area, BEEL devices with a planar TJ emitter can inject collector current as large as a few μA . The corresponding BEEL signal is strong enough for a wavelength-resolving spectrometer analysis. In the case of STM injection, however, the typical collector current is 1–100 pA (with a tip tunnel current of a few nA), which is nearly six orders of magnitude smaller than the TJ devices. Therefore, practically speaking, only the total photon intensity is measurable using high-efficiency fiber optics and sensitive single-photon-counting detectors. Since these two configurations are complementary to each other, we prepared both devices terminated with a thin Au base layer for STM studies fabricated as in Ref. 4, and devices terminated with Al-Al₂O₃-Al tunnel junctions for wavelength analysis fabricated as in Ref. 3. All the devices are made from adjacent regions of the same wafer.

At room temperature, a collector leakage current (typically a few nA at a collector bias of 0.5 V) due to thermionic

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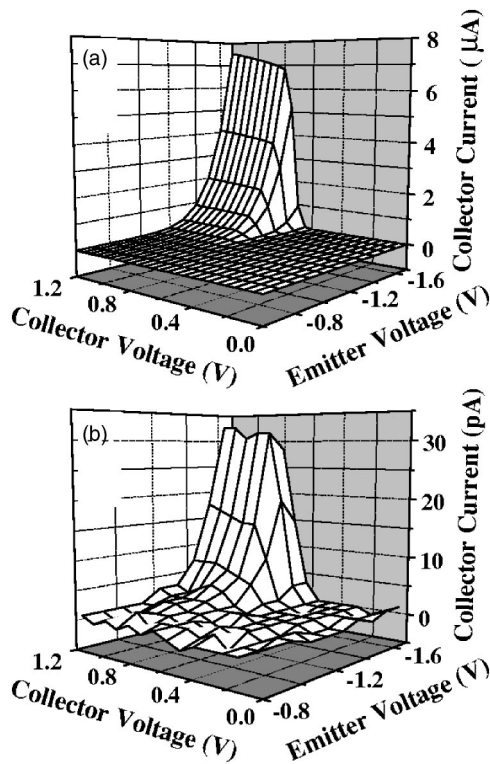


FIG. 1. $I_{collector}$ as a function of both $V_{emitter}$ and $V_{collector}$ at low temperature for the TJ BEEL device (a), and STM BEEL device at tunnel current of 4 nA (b).

emission produces a background luminescence signal. This leakage current is much larger than the injected ballistic electron current by the STM tip, making a complementary BEES measurement impossible at room temperature.⁴ Therefore, all the measurements are performed at low temperatures to freeze-out the leakage current and the accompanying background luminescence. Moreover, the luminescence efficiency of QDs are improved by lowering the temperature. The STM measurements are performed in a custom-designed Oxford Instruments Cryo-SXM system using mechanically-cut Pt-Ir tips. Luminescence is collected with a cleaved 400 μm , 0.39 numerical-aperture fiber placed in close proximity to the tunnel point. The luminescence signal is detected with a Si avalanche photodiode in single-photon-counting mode (Perkin-Elmer SPCM-AQR).⁴ To avoid the parasitic luminescence signal from resonant surface plasmon excitations in the Au film, in all STM measurements the tip bias is limited to $|V_{tip}| \leq 1.4$ V.⁴ Spectrometer measurements of TJ devices are performed as described in Ref. 3.

First, the collector current spectroscopy is examined. For planar TJ devices, Fig. 1(a) shows a three-dimensional (3D) surface plot of the collector current ($I_{collector}$) measured at 77 K as a function of emitter voltage ($V_{emitter}$) and collector voltage ($V_{collector}$), over the range $0 \text{ V} < V_{collector} < 1.2 \text{ V}$ and $-1.7 \text{ V} < V_{emitter} < -0.6 \text{ V}$, with 25 mV resolution. At a constant $V_{collector} \geq 0.7 \text{ V}$, $I_{collector}$ is zero for $V_{emitter}$ smaller than the SB ($\approx -0.8 \text{ V}$). Beyond this threshold, the current increases similar to BEES. For this device, the emitter current ($I_{emitter}$) varies between $\approx 0.1 \text{ mA}$ at -0.6 V and $\approx 0.7 \text{ mA}$ at -1.6 V .¹² At a constant $V_{emitter} \geq \text{SB}$, $I_{collector}$ shows an abrupt turn on at $V_{collector} \approx 0.65 \text{ V}$, which continues to increase with $V_{collector}$ thereafter. As a comparison, Fig. 1(b) shows a 3D surface plot of BEES measured by STM at 83 K at a

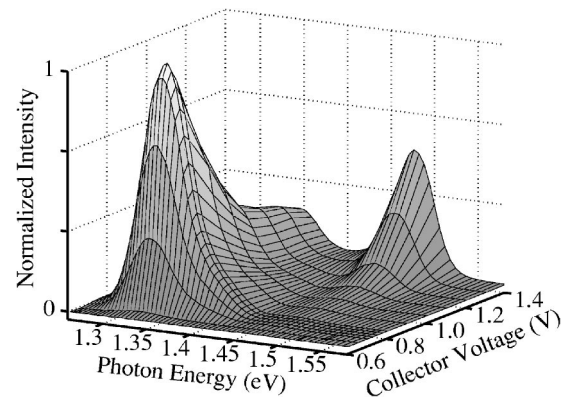


FIG. 2. $V_{collector}$ dependence of the wavelength spectrum taken with a planar Al-Al₂O₃-Al tunnel-junction device at 77 K.

constant tunnel current of 4 nA. The acquisition time for each curve is ~ 100 s. Since $I_{collector}$ by STM injection is much smaller than the planar TJ injection, the signal to noise ratio is deteriorated. However, the main features of the spectra reproduce that of TJ devices, with a nearly identical $V_{emitter}$ threshold at -0.8 V and $V_{collector}$ threshold at 0.65 V , respectively.

Figure 2 shows a representative 3D surface map of BEEL spectra from TJ devices as a function of photon energy and $V_{collector}$ measured at 77 K, with $V_{emitter} > \text{SB}$. At $V_{collector} \approx 0.65 \text{ V}$, a sharp turn-on of luminescence peaked near 1.34 eV is observed. This peak matches the reported ground-state electroluminescence peak of InAs QDs with similar structural parameters.¹³ The intensity of this peak is maximized at $V_{collector} \approx 0.78 \text{ V}$, which then decreases for higher collector voltage. A 20 meV/V linear shift of the peak energy as a function of $V_{collector}$ is observed, which is the signature of the quantum-confined Stark effect.¹⁴ For $V_{collector} \geq 1 \text{ V}$, a second photon peak at 1.48 eV is observed. This energy matches GaAs band-edge luminescence, with no $V_{collector}$ -dependent emission shift observed.

Figure 3 shows the $V_{collector}$ dependence of the spectrally integrated luminescence intensity of the TJ device data in Fig. 2, compared to a typical STM BEEL spectrum measured at 11 K with a constant tip voltage of -1.4 V and tunnel current of 4 nA. Clearly the main features of these two spectra agree: a sharp QD luminescence turn on at $V_{collector} \approx 0.65 \text{ V}$, followed by a maximum of luminescence signal at $V_{collector} \approx 0.78 \text{ V}$ and a subsequent slow decrease. The luminescence intensity starts to increase again at $V_{collector} > 1 \text{ V}$,

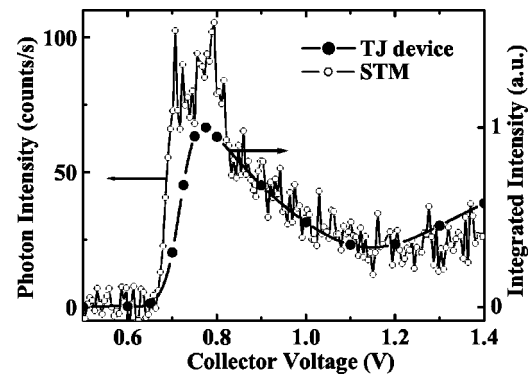


FIG. 3. $V_{collector}$ dependence of the integrated luminescence intensity (solid circles) of the TJ device data in Fig. 2 compared to a typical STM BEEL spectrum (open circles).

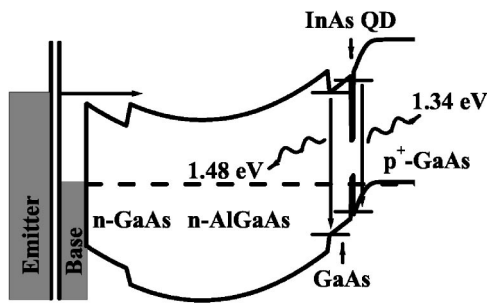


FIG. 4. Schematic band diagram of the BEEL system with unbiased collector, and $eV_{emitter} > SB$. The Fermi level is indicated by the dashed line. Luminescence from the dots and the GaAs spacer layer at 1.34 and 1.48 eV, respectively, are indicated by the vertical transition arrows.

which is attributed to be from GaAs, as suggested by the results from the TJ device (Fig. 2). Without the use of the planar TJ as an equivalent system with much higher luminescence output, the STM BEEL results would be difficult to interpret. The added wavelength information acquired from TJ devices allows us to assign contributions from two separate sources of luminescence in STM measurements.

To understand the BEEL spectra, Fig. 4 shows a schematic equilibrium band diagram of the InAs QD heterostructure, with the QDs modeled as a continuous layer. At the metal-semiconductor interface, the Fermi level is pinned by the SB approximately 0.8 eV below the conduction-band minimum, whereas the Fermi level in the heavily p -type region and the adjacent QD layer is pinned close to the valence-band maximum. This introduces a high built-in potential barrier that prevents ballistically injected electrons from entering the dots. A collector voltage beyond a threshold of 0.65 V nulls this barrier and allows electrons to radiatively recombine with holes in the dots. At even higher $V_{collector}$ (≥ 1 V), however, holes gradually leak into the GaAs spacer grown on top of QDs, which causes GaAs band-edge luminescence at 1.48 eV. No Stark shift is observed in this peak due to the absence of quantum confinement in the GaAs spacer layer, which also excludes the possibility of luminescence from the InAs wetting layer.¹⁵

In summary, we have presented low-temperature BEEL and BEES measurements of three-terminal heterostructure

devices embedding optically active InAs QDs. The QD luminescence from ballistic electron injection with STM is justified by the wavelength spectroscopy from solid-state tunnel-junction devices. By freezing out the leakage current, we are able to measure the tip-injected collector current in a biased BEEL device. Our results pave the way to a simultaneous imaging of the surface topography, local electron transport, and luminescence of semiconductor heterostructures.

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¹¹The dots are formed by depositing 1.7 ML of InAs at 530 °C and annealed for 30 s, then they are covered at 530 °C with a 1 nm GaAs cap followed by a second 30 s anneal before capped by the 5 nm undoped GaAs spacer layer.

¹²For TJ devices, the current transfer ratio $I_{collector}/I_{emitter}$ instead of the absolute value of $I_{collector}$ should be used in comparison to STM BEES.

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