

Ballistic electron emission luminescence

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We describe the design, fabrication, and operation of a GaAs-based heterostructure device which emits band gap luminescence from solid-state tunnel-junction ballistic injection of electrons with sub-bandgap energy. We find that, due to energy conservation requirements, a collector bias exceeding a threshold determined by the Schottky barrier height and sample band gap energy must be applied for luminescence emission. The consequences of these results for a hybrid scanning-probe microscopy and spectroscopy combining both ballistic electron emission microscopy and scanning tunneling luminescence are emphasized. © 2003 American Institute of Physics. [DOI: 10.1063/1.1584524]

Since its invention in 1981, the scanning tunneling microscope (STM)¹ has been improved and refined in various ways by adding extra channels of information and correlating it to the topography. For instance, the STM was converted to a three-terminal method by introducing a grounded third electrical contact to collect transmitted current in the development of ballistic electron emission microscopy (BEEM) and its associated spectroscopy (BEES) by Kaiser and Bell in 1988.² Since then, BEEM/BEES has been widely used to study metal–semiconductor interfaces and buried heterostructures.^{3–7}

Another extension of the STM has been in the direction of optics, by including luminescence information associated with either inelastic tunneling⁸ or impact ionization in a semiconductor sample. This application is called scanning tunneling luminescence (STL),^{9,10} and has been used extensively in microscopy mode to study surface plasmons of metal films^{11,12} and semiconductor minority carrier recombination.^{13,14} It has also proved to be a useful spectroscopic technique that is complementary to BEES.¹⁵

Because of the success of these two methods, and the clear benefit of adding extra channels of information to the STM, a hybrid microscopy which correlates topography with not only transmitted current as in BEEM, but also with luminescence like STL, would be very useful. This unique tool, called ballistic electron emission luminescence microscopy, or BEEL microscopy, would be particularly advantageous in the study of buried luminescent layers, just as

BEEM allows the study of transport through buried semiconductor heterostructures.

In this letter, we discuss the feasibility of this proposed method by examining the behavior of a BEEL device which employs the same luminescence mechanism as the STM-based configuration. However, since the emitter currents are far greater than in a STM measurement,^{16,17} the device will more clearly elucidate the parameters required for successful BEEL microscopy.

Figure 1(a) shows a schematic BEEM/BEES conduction band profile, with an unbiased collector. At an emitter voltage (V_{emitter}) below the Schottky barrier (SB), the tunneling current is transferred to ground by the base contact. Above the SB threshold, a significant fraction (10^{-3} – 10^{-1}) of the tunnel current travels ballistically through the thin base metal and into the semiconductor collector to ground.² It seems reasonable to expect that electrons ballistically injected just above the Schottky barrier into the *p*-type region of a semiconductor should recombine radiatively with holes and emit band gap (E_g) luminescence.

Although band gap luminescence is observed at voltages in the impact ionization regime¹⁵ (where $eV_{\text{emitter}} > E_g$, far above the SB), ballistic electrons with energies just above the SB, but significantly below E_g , cannot recombine radiatively in a normally unbiased sample. To illustrate and emphasize this point, we draw an analogy between ballistic electron emission with a tunnel junction (BEEM) and electron injection via internal photoemission (IPE).^{18–21} In the analogy we draw, instead of using an emitter voltage to give electrons ballistic energy (eV_{emitter}) as in BEEM, incident photoexcitation is used to provide energy, $h\nu$, to the elec-

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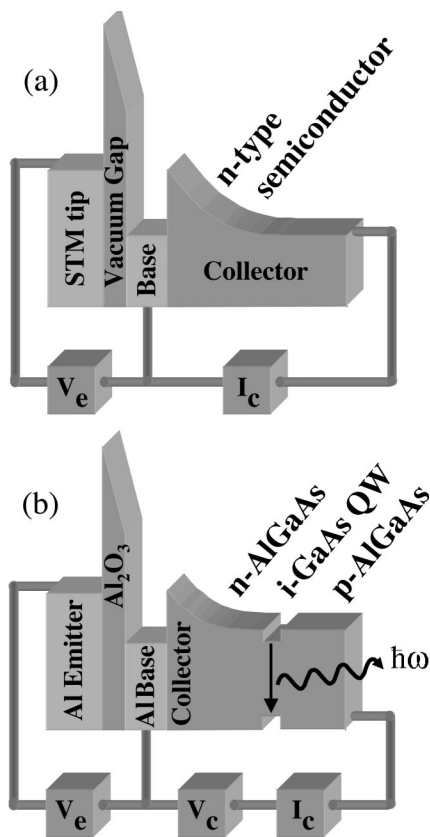


FIG. 1. Schematic conduction band diagrams of the conventional ballistic electron emission microscopy/spectroscopy system, with unbiased collector (a), and the BEEL device, with specifically doped heterostructure and biased collector (b).

trons. Clearly, the incident illumination injects photocurrent into the semiconductor only when $h\nu > SB$, just as a tunnel bias results in injected current only when $eV_{\text{emitter}} > SB$.

Optical up-conversion from $E_g > h\nu > SB$ photons to higher-energy photons with $h\nu \approx E_g$ does not take place in an unbiased IPE device due to energy conservation.²² For the same reason, a BEEL microscopy sample will not emit band gap luminescence when electrons with energies just over the SB are injected into the semiconductor, unless additional energy is added to the system. The difference in energy between the input energy from hot electrons, SB, and the output energy carried by emitted photons, E_g , is provided by positively biasing the collector with respect to the base ground.

Figure 1(b) shows the schematic band diagram of a BEEL device. In contrast to the BEEM band diagram schematic [Fig. 1(a)], the Al contact replaces the STM tip as emitter, and the Al_2O_3 replaces the vacuum gap as a tunnel barrier. An independent collector bias, as discussed earlier, can be applied and adjusted across the sample.

Our heterostructure device was grown via molecular beam epitaxy with the following structure: heavily doped p -type GaAs substrate, 300 nm p -type GaAs buffer layer doped to $5 \times 10^{18} \text{ cm}^{-3}$, 300 nm p -type $\text{Al}_{0.30}\text{Ga}_{0.70}\text{As}$ doped to $5 \times 10^{18} \text{ cm}^{-3}$, 10 nm GaAs undoped quantum well (QW), 100 nm n -type $\text{Al}_{0.30}\text{Ga}_{0.70}\text{As}$ doped to $2 \times 10^{17} \text{ cm}^{-3}$, and a 20 nm n -type GaAs cap layer doped to $2 \times 10^{17} \text{ cm}^{-3}$. All n -type doping is with Si, all epitaxial p -type doping is with Be, and substrate doping is with Zn.

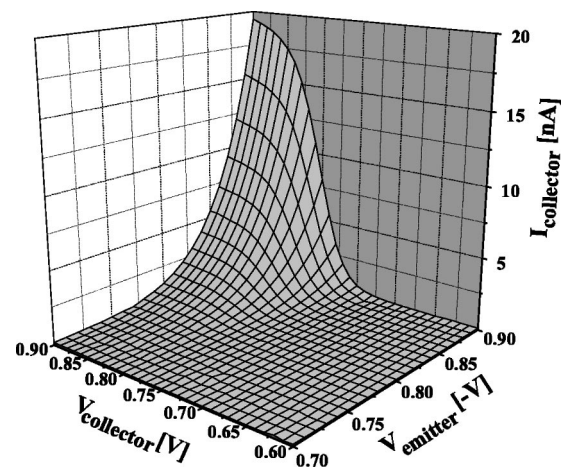


FIG. 2. Collector current ($I_{\text{collector}}$) measured as a function of both emitter bias (V_{emitter}) and collector bias ($V_{\text{collector}}$) for the BEEL device. A Schottky barrier of $\approx 0.8 \text{ V}$ is evident at constant collector bias.

The structure parameters were chosen to provide an n -type Schottky interface at the surface and a hole-rich recombination region in the otherwise undoped GaAs QW. The n -type surface doping is required so that the injected electrons have long lifetimes as majority carriers before recombining radiatively in the QW. The p -type doping level beneath the undoped QW must be significantly higher than that of the n -type region to compensate the electron population in the quantum well.

The wafer was processed using standard shadow-mask and photolithographic techniques. After cleaning the surface with dilute NH_4OH , 100 Å of Al was deposited via thermal evaporation at high vacuum to form a $500 \times 500 \mu\text{m}^2$ base Schottky contact. To grow the tunnel oxide, the sample was exposed for 90 s to an UV ozone lamp in air. Two $400 \times 100 \mu\text{m}^2$ stripes of 1200 Å Al were deposited via thermal evaporation, partially on a 1000 Å Al_2O_3 insulator pad for bonding. These conductors form two tunnel junctions on the base layer. The sample was then processed into device mesas $2 \mu\text{m}$ high and of area $900 \times 1000 \mu\text{m}^2$ by patterning with photolithography and etching with $\text{NH}_4\text{OH}/\text{H}_2\text{O}_2/\text{H}_2\text{O}$ 1:1:5 for 70 s.

Electrical contact to the collector substrate was made by cold pressing an In contact to the back surface. Wire bonds to the two Al stripes provide emitter and base contact after one tunnel junction was shorted. All measurements were done in an optical cryostat at 150 K to reduce thermal Schottky leakage below the measurement sensitivity (10 pA). The luminescence was collected with a 0.44 numerical aperture lens, and the spectra were recorded with a Thermo-Oriel MS257 spectrograph with a cooled charge coupled device camera and a diffraction grating with 150 lines/mm and a blaze wavelength of 800 nm.

Electrons were injected into the collector by negatively biasing the emitter with respect to the base via an emitter voltage (V_{emitter}). A schematic conduction band diagram of this configuration is shown in Fig. 1(b). The nonzero collector bias ($V_{\text{collector}}$) and specifically doped heterostructure collector are the significant differences between this BEEL device and conventional BEEM [Fig. 1(a)]. Figure 2 shows a surface plot of the collector current as a function of the two

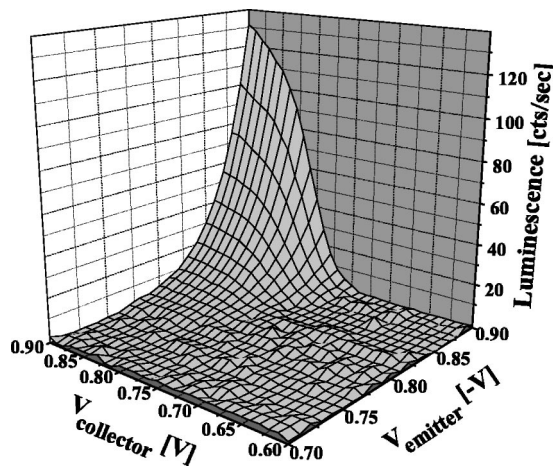


FIG. 3. Ballistic electron emission luminescence as a function of both emitter bias (V_{emitter}) and collector bias ($V_{\text{collector}}$) for the BEEL device. Significant band gap luminescence is observed just above the Schottky barrier. This luminescence was taken simultaneously with the collector current data shown in Fig. 2.

independent parameters (V_{emitter} and $V_{\text{collector}}$) over the range $0.6 < V_{\text{collector}} < 0.9$ V and $-0.9 < V_{\text{emitter}} < -0.7$ V, with 10 mV resolution. At a constant $V_{\text{collector}} > \approx 0.8$ V, the collector current ($I_{\text{collector}}$) is zero for V_{emitter} below the SB (≈ 0.8 V), but increases past this threshold, as in BEES. For this device, the emitter current varies between ≈ 2.5 mA at -0.7 V and ≈ 3.75 mA at -0.9 V.

In Fig. 3, we present the magnitude of the band gap (approximately 1.5 eV) luminescence which was collected simultaneously with the collector current data shown in Fig. 2. Luminescence is observed only when $V_{\text{collector}}$ exceeds a threshold approximately equal to the difference between the SB energy and the emitted photon energy. This verifies the energy-conservation argument presented earlier.

We now discuss these results in the context of the development of BEEL microscopy. The collector current in BEEM experiments on GaAs Schottky diodes is typically orders of magnitude lower (1–10 pA in the range studied) than observed in the heterostructure device (≈ 10 nA) presented in this work. It is clear from a correlation of Figs. 2 and 3 that the efficiency of luminescence emission and collection is on the order of $1-10$ photons s^{-1} nA^{-1} . To obtain a reasonable signal/noise ratio, a BEEL system in microscopy mode must therefore collect luminescence for much longer than 1 s at each point in a raster scan. Typical microscopy scans have on the order of 10^4-10^5 measurement points. At these efficiencies, one image would take many hours.

In the device, the Al emitter shadows the luminescence. Since the STM uses an atomically sharp emitter probe, a higher collection efficiency is expected. However, there are other ways to increase signal and reduce the required time for image collection. The collection efficiency can be improved by using one or more high numerical aperture fibers in close proximity to the tunnel point,²³ or by using a thinner base metal layer to reduce signal attenuation. Also, if spectroscopic analysis is not required, the emitted luminescence can be directly detected using a photomultiplier or avalanche photodiode. Such an arrangement would provide signifi-

cantly higher signal by circumventing the relatively low throughput of the spectrograph. The luminescence efficiency may also be improved by cooling the sample to temperatures lower than those used in the present work. Increasing the luminescence signal by two orders of magnitude by implementation of these concepts will allow feasible measurement of a BEEL microscopy image in ≈ 100 s, a typical time for a topographic STM scan.

In conclusion, we have reported on progress toward the development of a microscopy which combines the features of both BEEM and STL. This alternative STM-based method, BEEL microscopy, requires a specifically doped heterostructure sample and the addition of a collector bias which exceeds the threshold determined by conservation of energy in the system. We expect that if the luminescence collection efficiency can be improved beyond what these initial device-mode observations suggest, this microscopy could be particularly useful in spatially resolved studies of optically active layers such as quantum wells.

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- ¹G. Binnig, H. Rohrer, G. Gerber, and E. Wiebel, *Phys. Rev. Lett.* **49**, 57 (1982).
- ²W. J. Kaiser and L. D. Bell, *Phys. Rev. Lett.* **60**, 1406 (1988).
- ³G. N. Henderson, T. K. Gaylord, E. N. Glytsis, P. N. First, and W. J. Kaiser, *Solid State Commun.* **80**, 591 (1991).
- ⁴D. L. Smith and Sh. M. Kogan, *Phys. Rev. B* **54**, 10354 (1996).
- ⁵T. Sajoto, J. J. O'Shea, S. Bhargava, D. Leonard, M. A. Chin, and V. Narayanamurti, *Phys. Rev. Lett.* **74**, 3427 (1995).
- ⁶J. Smoliner, R. Heer, and G. Strasser, *Phys. Rev. B* **60**, R5137 (1999).
- ⁷For a recent review, see V. Narayanamurti and M. Kozhevnikov, *Phys. Rep.* **349**, 447 (2001).
- ⁸R. W. Rendell and D. J. Scalapino, *Phys. Rev. B* **24**, 3276 (1981).
- ⁹J. K. Gimzewski, B. Riehl, J. H. Coombs, and R. R. Schlittler, *Z. Phys. B* **72**, 497 (1988).
- ¹⁰R. Berndt, *Scanning Microsc.* **9**, 687 (1995).
- ¹¹G. Hoffmann, J. Kliewer, and R. Berndt, *Phys. Rev. Lett.* **90**, 46803 (2003).
- ¹²Z. Wu, T. Nakayama, S. Qiao, and M. Aono, *Surf. Sci.* **415**, L1032 (1998).
- ¹³P. Renaud and S. F. Alvarado, *Phys. Rev. B* **44**, 6340 (1991).
- ¹⁴K. Yamanaka, K. Suzuki, S. Ishida, and Y. Arakawa, *Appl. Phys. Lett.* **73**, 1460 (1998).
- ¹⁵M. Kemerink, K. Sauthoff, P. M. Koenraad, J. W. Gerritsen, H. van Kempen, and J. H. Wolter, *Phys. Rev. Lett.* **86**, 2404 (2001).
- ¹⁶J. P. Spratt, R. F. Schwarz, and W. M. Kane, *Phys. Rev. Lett.* **6**, 341 (1961).
- ¹⁷R. Heer, D. Rakoczy, G. Ploner, G. Strasser, E. Gornik, and J. Smoliner, *Appl. Phys. Lett.* **75**, 4007 (1999).
- ¹⁸C. R. Crowell, L. E. Howarth, W. G. Spitzer, and E. E. Labate, *Phys. Rev.* **127**, 2006 (1962).
- ¹⁹A. Deneuville and B. K. Chakraborty, *Phys. Rev. Lett.* **28**, 1258 (1972).
- ²⁰C. W. Kao, C. L. Anderson, and C. R. Crowell, *Surf. Sci.* **95**, 321 (1980).
- ²¹L. S. Yu, Q. J. Xing, D. Qiao, S. S. Lau, K. S. Boutros, and J. M. Redwing, *Appl. Phys. Lett.* **73**, 3917 (1998).
- ²²K. J. Russell, I. Appelbaum, H. Temkin, C. H. Perry, V. Narayanamurti, M. P. Hanson, and A. C. Gossard, *Appl. Phys. Lett.* **82**, 2960 (2003).
- ²³M. Kemerink, J. W. Gerritsen, J. G. H. Hermesen, P. M. Koenraad, H. van Kempen, and J. H. Wolter, *Rev. Sci. Instrum.* **72**, 132 (2001).