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Vertically integrated optics for ballistic electron emission luminescence microscopy

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We have integrated a photon detector directly into a ballistic electron emission luminescence (BEEL) heterostructure, just below a luminescent quantum well. Results from solid-state metal-base hot-electron transistors fabricated with this collector design indicate that more than 10% of the photons emitted by the quantum well excite photoelectrons in the detector region. The improved photonic coupling and effective collection angle in this scheme improves the BEEL signal by many orders of magnitude as compared to far-field detection with the most sensitive single-photon counters, enabling BEEL microscopy in systems with no optical components. © *2005 American Institute of Physics*. [DOI: 10.1063/1.1861961]

In ballistic electron emission luminescence (BEEL), hot electrons injected by a tunnel junction across a Schottky barrier radiatively recombine with holes in a semiconductor *p*-*i*-*n* heterostructure, emitting band-edge luminescence.[1] When the source of hot electrons is a scanning tunneling microscope (STM) tip,[2] this process promises lateral resolution of luminescent layers buried far beneath the metal-semiconductor interface for imaging, characterization, and study of local light emission in light-emitting diode and semiconductor laser structures.[3,4]

Because the injected current is small in STM mode, the subsequent light emission is proportionately difficult to sense using far-field detection methods. We propose the use of a photodetector directly integrated into the BEEL heterostructure, enabling measurement of hot-electron-induced luminescence with the highest sensitivity possible.

The AlGaAs/GaAs semiconductor heterostructure collector design used in this work was based on the structure of previously studied BEEL devices.[1,3,5,6] Beneath the hot-electron collection layers and luminescent GaAs quantum well (QW), a 1 μm photon-absorption layer was grown between heavily doped *p*- and *n*-type material. To improve the sensitivity to photons emitted from the QW, the absorption edge of the photon detector was effectively lowered by fabricating it from an undoped superlattice (SL) of 20 periods of 40 nm GaAs/10 nm $In_{.05}Ga_{.95}As$.

The heterostructure device was grown via molecular-beam epitaxy with the following structure. A heavily doped *n*-type GaAs substrate, GaAs/InGaAs SL, and 100 nm *p*-type GaAs buffer layer doped to 5×10^{18} cm^{-3} form the photon detector. Next, 100 nm *p*-type $Al_{0.30}Ga_{0.70}As$ doped to 5×10^{18} cm^{-3}, 25 nm *p*-type $Al_{0.45}Ga_{0.55}As$ etch-stop layer doped to 5×10^{18} cm^{-3}, and 100 nm *p*-type $Al_{0.30}Ga_{0.70}As$ doped to 5×10^{18} cm^{-3} were grown. The thickness and composition of these p^+ layers is designed to ensure that hot electrons injected into the conduction band at the metal-semiconductor interface cannot enter the photon detection region to contribute to the photocurrent. On this p^+ region, a 5 nm undoped $Al_{0.30}Ga_{0.70}As$ spacer, 10 nm GaAs undoped QW, 5 nm undoped $Al_{0.30}Ga_{0.70}As$ spacer, 100 nm *n*-type $Al_{0.30}Ga_{0.70}As$ doped to 2×10^{17} cm^{-3}, and a 20 nm *n*-type GaAs cap layer doped to 2×10^{17} cm^{-3} form the BEEL collector. These latter layers differ from previously published BEEL device studies only by the thin undoped spacer layers on either side of the QW, which is intended to reduce donor-acceptor recombination pathways. All *n*-type doping is with Si, all *p*-type doping is with Be. The resulting unbiased band diagram is shown schematically in Fig. 1.

Previous work has shown that solid-state tunnel-junction hot-electron transistors are useful for modeling the spectroscopic features of BEEL seen in microscopy mode.[1,3] Specifically, the injected current is much larger and therefore the BEEL signal is proportionately easier to measure. Therefore, we use this substitution to examine the effectiveness of the

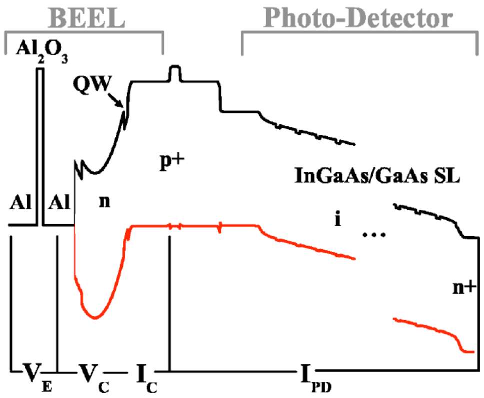

FIG. 1. Band diagram of vertically integrated device with BEEL region (left) and integrated photodiode (right), showing emitter voltage bias (V_E), collector voltage bias (V_C), collector current measurement (I_C), and photocurrent measurement (I_{PD}).

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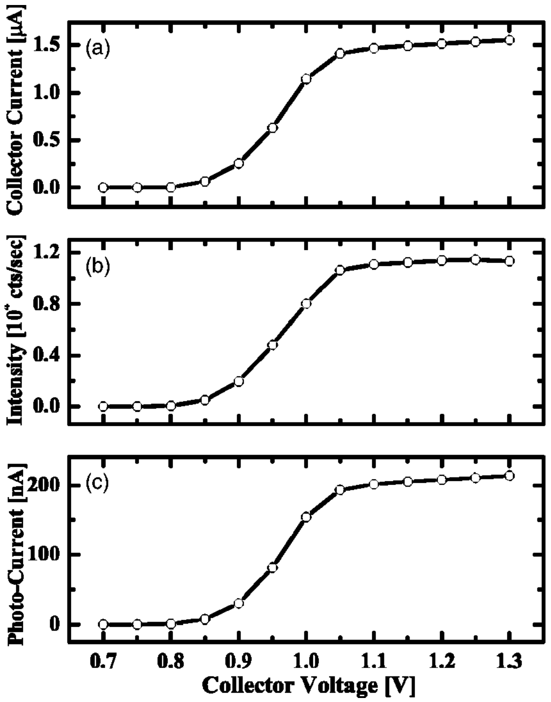

FIG. 2. Comparison of collector bias dependence of collector current (a), externally collected luminescence (b), and on-device photodiode photocurrent (c) at constant emitter voltage −1.5 V at 77K.

integrated photodetector. Our standard shadow-mask method for fabrication of metal-base transistors[1,5,7] was preceded by a lithographically defined etch down to the buried p^+ layer (collector) and subsequent contact with Au/Cr. Shadow-masked vacuum deposition of a thin (100 Å) Al base, UV ozone oxidation, and masked deposition of a thick (800 Å) Al emitter form the hot-electron tunnel-junction injector. After lithography and wet-etching for mesa definition, the devices were wire-bonded and measured in an optical cryostat at 77 K to eliminate thermionic leakage at the Al (base)/*n*-GaAs (collector) Schottky barrier under reverse bias.

The collector current spectrum as a function of the collector voltage bias under constant emitter voltage (−1.5 V) is shown in Fig. 2(a). The threshold between 0.9 and 1.0 V is similar to the collector current threshold at 0.8 V seen in Fig. 2 of Ref. 1. The in-plane resistance of the thin p^+ layer or contact resistance in this integrated optics device could result in a substantial bias drop and explain the subsequent slight increase in apparent threshold.

Photon emission from the GaAs QW accompanies the increase in collector current at the collector voltage threshold. Figure 2(b) shows the magnitude of the luminescent peak height collected with a lens and fiber and detected with a spectrometer and CCD. Again, this result is consistent with the relationship between collector current and luminescence intensity seen in Ref. 1. As discussed in that work, a collector bias supplying potential energy in excess of the difference between the band gap and the Schottky barrier height is needed to satisfy energy conservation in the conversion of hot-electron energy into photons.

The current induced from interband excitations by BEEL photons in the GaAs/InGaAs SL photodetector, recorded simultaneously with the data in Figs. 2(a) and 2(b), is shown in Fig. 2(c). The collector voltage dependence clearly mimics both the injected hot-electron current and the externally detected luminescence intensity. Moreover, the photocurrent is more than 13% of the collector current, indicating that a significant fraction of photons emitted by the GaAs QW cause photoexcitation in the photodetector. However, while the similarity in collector voltage dependence of all three of these signals is certainly evidence for photon detection, it does not completely rule out the possibility (albeit small) that the photodiode current is actually from leakage of electrons through the p^+ layer.

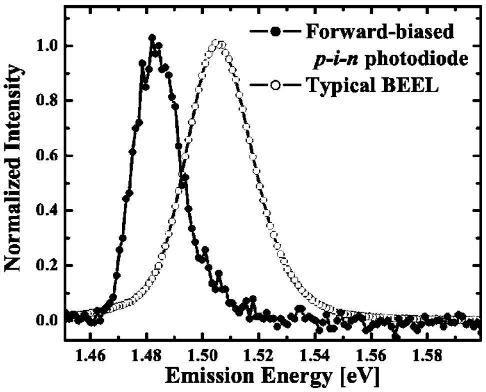

FIG. 3. Comparison of the BEEL emission line (open circles) with the forward-bias luminescence of the on-device photodiode (closed circles) shows that the absorption edge of the vertically integrated GaAs/InGaAs SL photodetector is below the average photon energy of BEEL from a GaAs QW at 77 K.

To eliminate this possibility, we present two pieces of evidence. First, the band edge of the photodetector is determined from forward-biasing it and measuring the spectrum of emitted photons as a result of radiative recombination of ohmically injected electrons and holes, as shown in Fig. 3. The emission line is clearly at a lower energy than the BEEL spectrum, which shows that the photodetector must be sensitive to the photons emitted from the GaAs QW.

The second piece of evidence is shown in Fig. 4. Simultaneous to the measurement of the data in Fig. 2, the photocurrent in the photodetector of an adjacent device on the chip was measured, even though the emitter and base were disconnected on that device. The geometry of this situation is

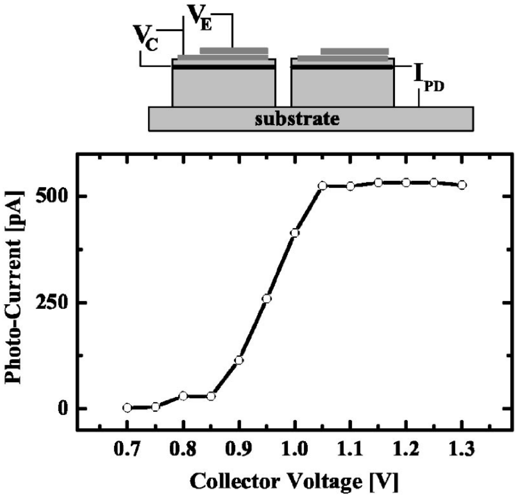

FIG. 4. Schematic representation of the measurement configuration (above) and collector bias dependence of the photocurrent of the photodiode adjacent to the operating BEEL device taken simultaneously with the data presented in Fig. 2.

shown in Fig. 4 (top). Since the mesa walls completely separate the hot-electron collector and photodiode, the signal must come from photon detection only and not electron leakage. As can be seen in Fig. 4 (bottom), this photodiode does detect a photon intensity proportional to the luminescence signal detected with conventional far-field techniques [e.g., Fig. 2(b)]. However, it is roughly 400 times weaker than the photocurrent measured with the photodiode directly beneath the luminescing QW [Fig. 2(c)] because the optical coupling is reduced. This strongly implies that the photodetector signal shown in Fig. 2 is due only to photoexcitation and not to electron leakage.

We can now analyze the results from the standpoint of our continuing development of BEEL as a microscopy method promising the capability of detecting the presence of spatially varying luminescent layers buried hundreds of nm below the surface. In microscopy mode, typical tunneling currents of 1–10 nA result in a collector current of 10–100 pA; this is expected to give 1–10 pA BEEL photocurrent, well within the detection range of high-gain amplifiers. More importantly, the direct integration of the photon detector into the device eliminates the need to accommodate optical components such as fibers or lenses in the microscope apparatus. The experiment needs only another electrical contact to the device for photocurrent measurement and a high-gain amplifier similar to that used for detection of the collector current.

In conclusion, we have simplified and strengthened the prospects for BEEL microscopy by incorporating the photon detector into the BEEL device itself. This has been shown to drastically improve the photon collection efficiency as compared to far-field detection and enables the use of photons to detect buried luminescent layers without any optics whatsoever.

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