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Electroluminescence from GaAs/AlGaAs Heterostructures in Strong in-Plane Electric Fields: Evidence for *k*- and Real-Space Charge Transfer

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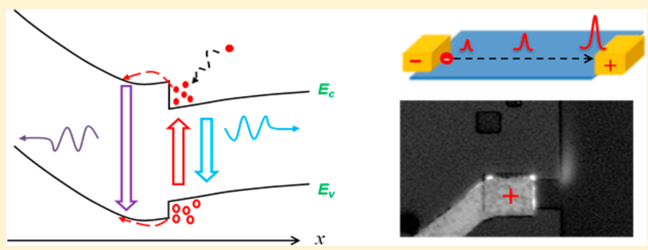

ABSTRACT: In the Gunn effect, which occurs in certain semiconductors in strong electric fields, electrons are driven out of a low-mass central valley into a heavy-mass side valley in *k* (momentum) space, ultimately resulting in negative differential resistance (NDR). Recently, there has been interest in the possibility of exploiting this phenomenon in heterostructured semiconductors, as a means to realize novel terahertz sources. Here, we demonstrate that a GaAs/AlGaAs heterostructure planar Gunn diode exhibits both NDR and electroluminescence (EL), the characteristics of which are consistent with the combined action of *simultaneous* *k*-space and real-space electron transfer. By making simultaneous electrical-transport and EL measurements, we reveal the following scenario as a function of the applied voltage. At sufficiently large bias, the onset of *k*-space transfer gives rise to NDR and results in the formation of traveling high-field domains. As each domain travels toward the anode, impact ionization taking place within it results in electron−hole pair generation and concomitant recombination. While some of this recombination takes place within the GaAs, it also occurs within the AlGaAs barrier after electrons undergo *real-space* tunneling into this layer from the GaAs. The real-space transfer is identified through the presence of a broad spectral peak in the EL consistent with the AlGaAs gap. Both the GaAs and AlGaAs EL peaks increase in intensity superlinearly with increasing bias, reflecting the nonlinear current−voltage characteristic of the device. Furthermore, we map out the spatial distribution of EL intensity in a long-channel device and observe the strongest EL near the anode, consistent with the notion that the high-field domain grows as it propagates from the cathode toward the anode. This planar Gunn diode provides a good platform for high-electric-field effect investigations in semiconductors under low bias and possible applications for terahertz technology.

KEYWORDS: *electroluminescence, Gunn effect, high-electric-field effects, real-space charge transfer*

Semiconductors in the presence of a high electric field exhibit a fascinating array of physical phenomena, the details of which have long been the focus of fundamental interest.[1−6] The novel aspects of field-driven carrier dynamics[7−20] also find broad practical application,[21,22] with a notable example provided by the use of the Gunn effect in microwave oscillators.[7−11] The basic phenomenon responsible for the Gunn effect is drift-velocity overshoot at high electric fields (a few kV/cm), which arises as a consequence of the transfer of high-energy electrons between different valleys of the conduction band (so-called "*k*-space transfer"). Accompanying this intervalley transfer are self-sustained current oscillations, whose operational frequency typically lies in the range of tens of GHz.[7−11]

Recently, there has been interest in the possibility of extending this operation into the terahertz (THz) band, and to therefore address the overall shortage of sources in this regime, by making use of *heterostructured* semiconductors.[23−28] A potential issue that arises in such structures is a competition between the *k*-space transfer required to produce self-sustained THz oscillations and the possibility of high-field-driven "*real-space* transfer"[29−33] of hot electrons between different layers of the heterostructure. Since the latter mechanism may interfere with the sustainable oscillations arising from *k*-space transfer, it is necessary to understand the interplay between these two phenomena in heterostructure devices under high-field

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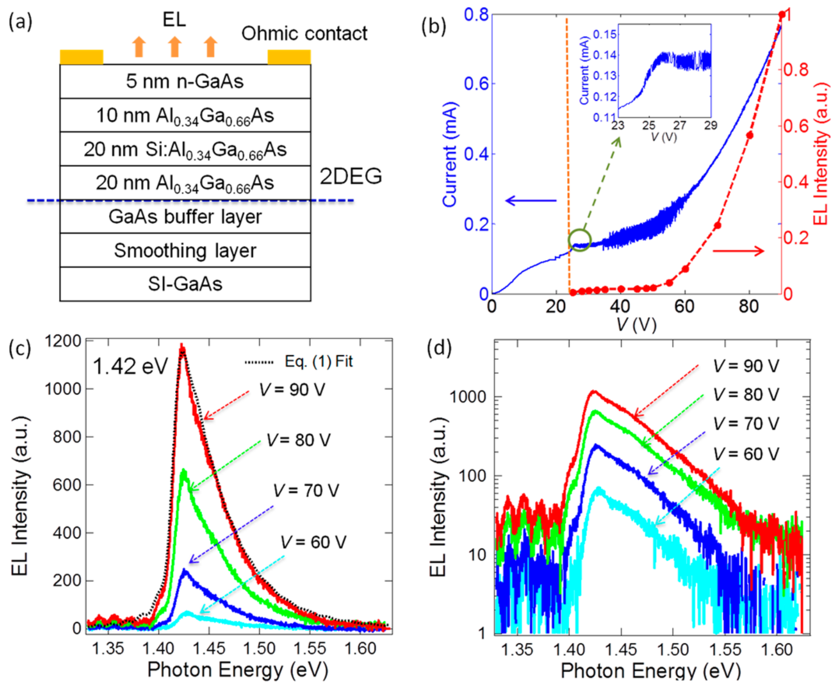

Figure 1. (a) Vertical structure of the GaAs/$Al_{0.34}Ga_{0.66}As$ heterostructure studied. Dashed line indicates the 2DEG position. (b) The bias dependence of the current (blue curve) and the normalized and integrated EL intensity (red curve) for the planar Gunn diode; the two quantities show almost the same threshold and superlinear dependence. Inset: Expanded view of the current−voltage relation in the region where the current saturation onsets. (c) EL spectra under different bias voltages. Black dashed line shows a fit to the spectrum according to eq 1. (d) The same spectra as in (c), but with EL intensity plotted on a logarithmic scale.

conditions. It is this issue that we explore in this report, where we investigate the signatures of real- and *k*-space scattering by identifying their distinct electroluminescence (EL) signatures in GaAs/AlGaAs heterostructures under high electric fields. The implication of these results is that proper attention will need to be paid to the design of heterostructured Gunn diodes, in order to suppress the real-space transfer while promoting the intervalley scattering desired for the Gunn oscillations.

Quite generally, the observation of high-field effects in semiconductors requires field strengths in excess of 100 kV/cm, a condition that must typically be satisfied by applying a large dc voltage across a short distance. The Gunn effect[7] provides a notable exception to this, allowing strongly nonuniform and intense electric fields to be realized with much lower applied voltages (in the range of a few volts to a few tens of volts). Above a threshold field that can be as low as 1 kV/cm, the kinetic energy of accelerated electrons becomes high enough for intervalley scattering, i.e., for *k*-space hot-electron transfer from the central (Γ) valley to the lowest-lying side valley (either the L or X valley). Since the effective mass of the central valley is much smaller than that of the side valley, the conductivity drops and negative differential resistance (NDR) occurs. This in turn leads to the formation of high-field domains,[9] the local field strength inside of which can be as high as 1 MV/cm, while the average field within the device is only at the level of a few kV/cm.[14] The nonuniform fields inside the domain accelerate electrons to a velocity that can cause impact ionization (depending on the band gap and mean free path), producing a cascading avalanche of electron−hole pairs and band-edge EL via subsequent carrier recombination.[23−26,34] Dependent upon the value of the applied voltage, the domain may travel periodically between the cathode (source) and anode (drain) of the device, at which point it collapses and a new domain is injected from the cathode. While this regime is of most interest for application to THz sourcing,[27,28] at even larger field strengths the domain may actually become pinned at the anode, producing strong EL in this region.

Here, we report on EL spectroscopy and electrical-transport studies of GaAs/AlGaAs heterostructure planar Gunn diodes. We observe strong EL from these devices, the intensity of which is found to increase superlinearly with increasing dc bias. Furthermore, we investigate the spatial distribution of the EL intensity in a long-channel device and show a clear concentration of this emission near the anode. As indicated above, this observation is consistent with the notion that the high-field domain grows as it propagates from the cathode toward the anode. In addition to EL from the GaAs band edge, we also identify a new EL feature coming from the band edge of AlGaAs, the presence of which suggests that GaAs-to-AlGaAs real-space charge transfer occurs at the same time as *k*-space intervalley transfer within the GaAs. Our observations therefore not only strengthen the understanding of the charge-transfer process in the planar Gunn diode but also provide insight into how to construct THz sources based on such diodes while overcoming potentially problematic real-space transfer.

■ RESULTS AND ANALYSIS

Figure 1a shows a cross section of the GaAs/AlGaAs heterostructure studied here, which was grown by molecular beam epitaxy on a semi-insulating GaAs substrate. This structure was modulation doped by introducing Si (at a density of ∼6.8×10^{17} cm^{-3}) into a 20 nm thick section of the $Al_{0.34}Ga_{0.66}As$ barrier layer. A two-dimensional electron gas (2DEG) was formed on the GaAs side of the heterointerface, as indicated by the dashed line in Figure 1a. Alloyed ohmic contacts were formed by depositing a Ni(8 nm)/Ge(24 nm)/

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Au(54 nm)/Ni(14 nm)/Au(100 nm) composite on the GaAs cap layer and then annealing at 480 °C. The channel length of the device was ~360 μm. The electron density and low-field mobility of this 2DEG at room temperature, under which condition the experiments reported here were performed, were 3×10^{11} cm^{-2} and 8×10^{3} cm^2/(V s), respectively, with a corresponding mean-free path of 70 nm.

The blue line in Figure 1b shows a typical current−voltage ($I-V$) curve of the planar Gunn diode and exhibits strong nonlinearity arising from high-field domain formation in the Gunn effect. Most notably, beyond a bias voltage $V \approx 25$ V, the current begins to saturate (Figure 1b inset), behavior that is attributed to the negative differential mobility induced by intervalley scattering.[10,11] In addition, the current shows strong fluctuations and self-sustaining oscillations, features that are commonly associated with the formation of traveling high-field domains.[7,9,35] When electrons gain sufficient kinetic energy from the field within the domain, impact ionization ensues and EL is observed. The intensity of the EL measured by collecting the top-surface emission (see Methods) is plotted as a function of V as a red solid line in Figure 1b. The EL clearly has the same threshold bias voltage as the current instability (blue line) and exhibits the same superlinear dependence upon the bias voltage. The estimated threshold electric field generated across the device for an applied voltage $V \approx 25$ V and *under the assumption of a uniform electric field* is just ~700 V/cm, very much lower than the GaAs breakdown field (~10^5 V/cm) required[36] for impact ionization and EL; thus, the observation of EL provides very strong evidence for the existence of high-field domains in our device.

For further insight into its origins, we have spectrally resolved the EL using a spectrometer (see Methods). Figure 1c shows EL spectra for a device under different bias voltages corresponding to the NDR region. A pronounced peak due to emission from the GaAs layer is observed, with a peak photon energy of 1.42 eV, which is very close to the GaAs bandgap. The spontaneous emission spectral distribution function $R_{spon}(h\nu)$ within the Maxwell−Boltzmann approximation can be written as[37]

$$R_{spon}(h\nu) = K_{spon}(h\nu - E_g)^{0.5} \exp\left(-\frac{h\nu - E_g}{k_B T}\right) \quad (1)$$

where K_{spon} is the spontaneous emission constant, E_g is the band gap of GaAs, and k_B is the Boltzmann constant (1.38×10^{-23} m^2 kg/s^2 K). The observed EL spectrum agrees well with this form, as indicated by the comparison for $V = 90$ V in Figure 1c. The exponential tail ("Boltzmann tail") on the high-energy side of the EL data can be more clearly seen as a straight line when plotting the EL intensity on a logarithmic scale, as shown in Figure 1d. This further confirms the appropriateness of using eq 1 in our analysis.

In addition to obtaining spectral information on the EL, as shown in Figure 2, we have also investigated its spatial distribution in a long-channel device. This reveals a strongly nonuniform character to the emission, which exhibits a "unipolar" distribution that is strongly concentrated near the anode. As noted already, when the applied bias exceeds the threshold required for the Gunn effect, the negative differential velocity of energetic electrons results in the formation of a high-field domain. The domain arises from a process of positive feedback, in which increasing charge accumulates within this region as it propagates from the cathode to the anode. The field associated with the domain therefore reaches its largest value at the anode, and the strongest EL intensity can be expected near this contact. Indeed, for sufficiently high field conditions, the domain can become pinned at the anode,[7−11] and the transition to this state is indicated by the strong suppression of the current noise that is observed near 65 V in the $I-V$ curve of Figure 1b. The data of Figure 2 were actually obtained in this regime, for an applied voltage of ±70 V, and show the unipolar EL mentioned above, consistent with the presence of a locally enhanced electric field near the anode. Further enhancing the visibility of the EL near this contact is the low mobility of holes generated by impact ionization near the anode.[23] In the two different panels of Figure 2, we compare the EL observed by reversing the polarity of the anode and cathode. In both cases, the EL is observed near the anode, confirming the details of the discussion above. The exact distribution of the EL is quite inhomogeneous, however, something that is once again found in studies of the Gunn effect in bulk semiconductors.[7−11] The essential point here is that the nonuniform character of the alloyed contacts results in the domain becoming pinned at localized "hot spots", where the EL similarly originates. We emphasize, however, that in both panels of Figure 2 the imaging confirms that the EL signal occurs only within the lateral regions that contain the 2DEG, which suggests that the impact ionization process is initiated by hot electrons in this two-dimensional layer.

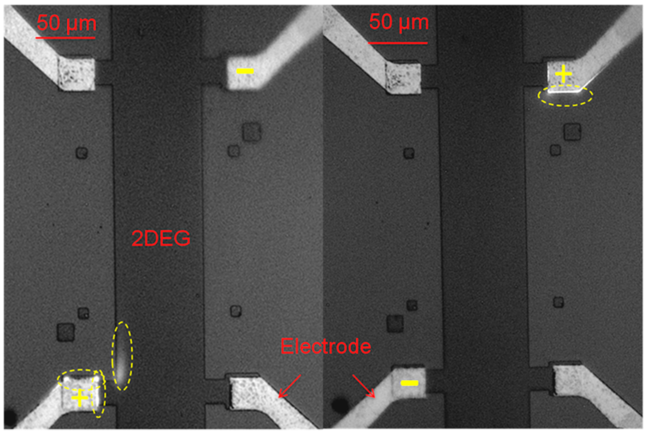

Figure 2. Microscope image of EL spatial distribution under different current polarity ($V = 70$ V). The positive (negative) sign denotes the anode (cathode). The dark Hall bar contains the 2DEG, while the other regions are completely etched away. The four bright areas are the ohmic electrodes. The dashed circles indicate where the EL is occurring.

Having addressed the issue of the spatial location of the EL, we now return to an analysis of its spectral content. As we show in Figure 3a, along with a sharp peak near 1.42 eV, the EL also exhibits a much broader peak from the $Al_{0.34}Ga_{0.66}As$ layer at ~1.84 eV. The spectrally integrated EL intensity is plotted as a function of the bias voltage in Figure 3b, where we normalize the intensity of the two emission features relative to their values at the highest bias voltage (90 V). It can be clearly seen from this figure that these two signals are strongly correlated to each other, emerging at the same threshold voltage and increasing at the same rate.

Based on our observations and analysis, we propose the model depicted schematically in Figure 4 to explain the two-peak EL spectra. In the GaAs/AlGaAs heterostructure, the 2DEG is initially formed as a conductive layer in the triangular

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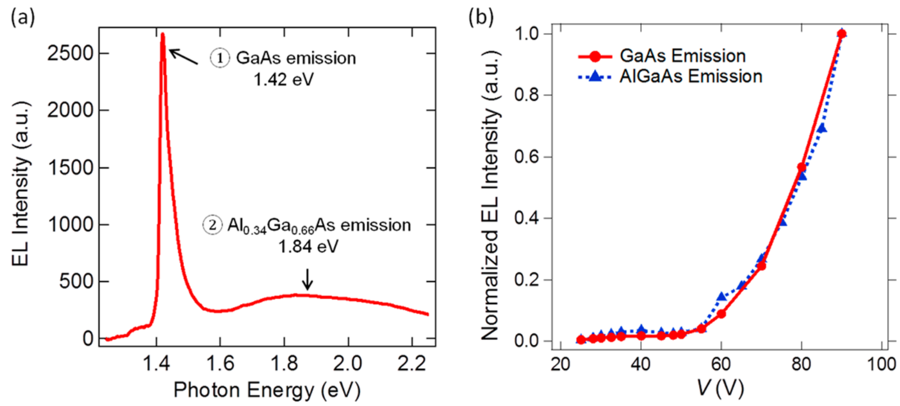

Figure 3. (a) Representative EL spectrum for the GaAs/AlGaAs planar Gunn diode at a bias of 90 V. Two distinct EL peaks are observed and are attributed to emission from the GaAs and AlGaAs layers. (b) Normalized and integrated EL intensities of the GaAs and AlGaAs EL peaks as a function of bias voltage, indicating the close correlation of these two signals.

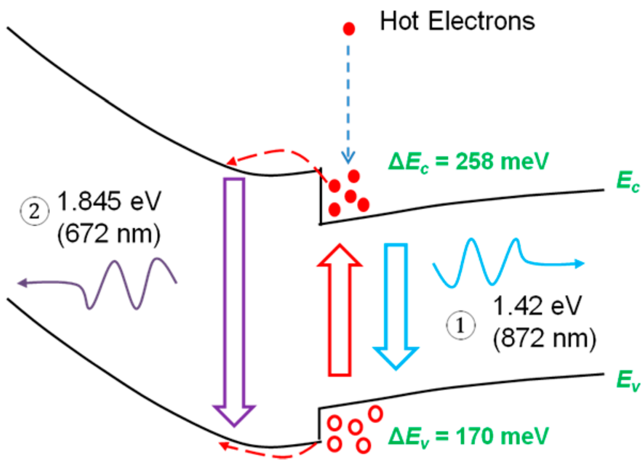

Figure 4. Proposed model for the origins of the two-peak EL spectrum, based on a combination of *k*-space and real-space transfer.

potential well on the GaAs side of the interface. When the Gunn effect occurs, a high electric field domain forms and electrons in the potential well are accelerated to high kinetic energy. Such hot electrons in the high-field domain induce impact ionization in the GaAs, which leads to the generation and recombination of electron−hole pairs, corresponding to the EL emission peak at 1.42 eV. However, the cascaded generation of electron−hole pairs by impact ionization also increases the quasi-Fermi energies, producing a finite probability for real-space tunneling of hot electrons and holes into the adjacent AlGaAs barrier. Because of this real-space transfer, recombination occurs in the AlGaAs layer also, giving rise to the observed second peak at ∼1.84 eV. The strong broadening of this peak compared to the much narrower feature due to the GaAs emission most likely reflects the role of the alloy-disorder broadening in the AlGaAs barrier.[38]

CONCLUSIONS

In conclusion, we have performed a simultaneous study of the electrical-transport and EL properties of a GaAs/AlGaAs heterostructure planar Gunn diode. We identified a new EL feature arising from the band edge of AlGaAs, along with EL from the GaAs band edge, which suggests that GaAs-to-AlGaAs real-space charge transfer occurs at the same time as *k*-space intervalley transfer. The EL intensity due to both of the processes increased superlinearly with increasing bias voltage and showed good consistency with the *I*−*V* characteristics of the device, with the same threshold voltage for the Gunn effect and superlinear bias voltage dependence. The spatial distribution of EL mapping further confirmed the presence of traveling high-field domains that propagate from the cathode to the anode, inducing the strongest local electric fields near the anode. As noted in the introduction, the motivation for this study comes from the need to understand the nature of hot-electron scattering processes in 2DEGs and their potential impact on the development of THz sources. Our results here show that in heterostructure-based systems of interest for THz technology the intervalley transfer of interest for THz generation may be degraded by the loss of electrons that are directly injected into the surrounding barriers. The successful development of such THz sources should therefore include strategies to suppress this real-space transfer process, most realistically by controlling the Al content of the barrier layer(s) to maximize its strength. Under such conditions, 2DEG-based planar Gunn diodes should provide a good platform for possible applications for THz sources.

METHODS

Electroluminescence Measurements. EL spectra were collected with a multimode optical fiber placed on top of the device and analyzed with a grating spectrometer equipped with a liquid nitrogen cooled charge-coupled-device (CCD) camera. EL mapping was performed by collecting the light emitted from the device with a 10× objective lens in a commercial optical microscope, equipped with a sensitive black-and-white CCD camera with controlled exposure times.

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Notes

The authors declare no competing financial interest.

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