Photon emission from avalanche breakdown in the collector junction of GaAs/AlGaAs heterojunction bipolar transistors

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The base-collector junction of GaAs/AlGaAs single heterojunction bipolar transistors has been observed to emit light at avalanche breakdown. The spectral distribution curve exhibits broad peaks at 2.03 and 1.43 eV, with the intensities dependent upon the reverse current. These observations suggest that electrons, excited to the upper conduction band by the field, lose their energy by impact ionizing electron-hole pairs and producing the 2.03 eV light, which corresponds to the threshold energy for electron impact ionization. The band-edge emission is the result of direct-gap free-carrier recombination and self-absorption of the high-energy transition.

Avalanche impact ionization and the behavior of electrons and holes under high electric fields in a semiconductor *p-n* junction have been the subject of intensive research since the earliest stages of semiconductor development.[1–4] Light emission associated with electron-hole recombination from reverse-biased *p-n* junctions has been reported in Si,[5–8] Ge,[9] SiC,[10] GaP,[11] InP, and GaAs.[12] While experimental and theoretical investigations in this area have focused primarily on silicon, the GaAs material has gained increasing interest due to its wide applications in impact-avalanche transit-time (IMPATT) diodes, GaAs/AlGaAs heterojunction devices such as bipolar transistors and modulation-doped field-effect transistors, and high-efficiency and fast-response photodetectors for fiber-optic communications.

A number of experimental and theoretical studies on the impact ionization rate and the threshold energy for avalanche multiplication in GaAs have been reported.[13–18] Using energy and momentum conservation considerations and a parabolic energy-momentum relationship around the valence and conduction band minima, Hauser[13] calculated a threshold energy for carrier multiplication E_{ie} in GaAs of about $1.5E_g$. Anderson and Crowell[14] presented a more general theory to calculate ionization threshold energies, reporting respective electron and hole ionization energies of $E_{ie} = 2.1$ eV and $E_{ih} = 1.7$ eV along the $\langle 100 \rangle$ direction of GaAs. Experimentally, Logan *et al.*[4] deduced a threshold energy $E_{ie} = 1.7 \pm 0.3$ eV from a best fit of ionization rates to the theory of Baraff.[19]

In this letter we report the observation of light emission from the collector-base junction of a GaAs/AlGaAs single heterojunction bipolar transistor (HBT) at breakdown. The photoemission spectrum of the reverse-biased junction is presented, and an analysis of the observed emission peaks is discussed.

The HBTs studied in the present investigation were grown by molecular beam epitaxy on Si-doped (100) oriented GaAs. A 1.0-μm-thick n^+-GaAs collector contact layer, doped 10^{18} cm^{-3} with Si, was grown first, followed by the 0.4-μm-thick *n*-GaAs collector layer, doped 5×10^{16} cm^{-3} with Si. The p^+-GaAs base layer of the investigated structure was 0.2 μm thick, doped 2×10^{18} cm^{-3} with Be. Grading to $Al_xGa_{1-x}As$ ($x = 0.15$), a 0.2-μm-thick emitter was grown, doped 10^{18} cm^{-3} with Si. Finally, a heavily doped 0.2-μm-thick n^+-GaAs emitter cap layer was grown.

After epitaxial growth, self-aligned HBTs with different device dimensions were fabricated by standard wet chemical etching techniques. *n*-type contacts to the emitter and collector layers, and *p*-type contact to the base layer were formed by evaporating AuGe/Ni/Au and AuBe contacts, respectively. Polyimide was then deposited, vias etched to the metal contacts, and Ti/Au overlay metal evaporated.

Shown in Fig. 1(a) is a top view of the fabricated HBT device. (The label *E* identifies the emitter contact pad, from which extends a single emitter finger, while the label *B* identifies the base and its two adjacent contact fingers.) Biasing the device of Fig. 1(a) beyond breakdown ($BV_{CBO} = 13$ V), we present in Figs. 1(b) a photograph of light emission from the 18×33 μm^2 collector-base junction at a reverse breakdown current of $I_C = 3.0$ mA. In the presented picture, breakdown extends around the entire periphery of the base mesa structure—obviously no light emission is observed through the overlay contact fingers. Note that at lower breakdown currents light emission first occurs at the corners of the base mesa then along the length of the mesa, before extending around the entire periphery, as shown. At even higher breakdown currents, light emission from the junction is observed through regions of the exposed base surface.

It is well known that light emission at breakdown of a *p-n* junction results from the direct recombination between essentially free holes and electrons in the breakdown region of the *p-n* junction. While local lattice heating cannot be ruled out, the temperature required to produce the observed light emission is estimated at about 2000–3000 K, a temperature that would melt the crystal, damaging the device catastrophically. In our investigated devices, light emission from the reverse-biased junction was in fact "reversible" with no resultant degradation in device performance.

Shown in Fig. 2 is the spectral distribution curve of the reverse-biased GaAs base-collector junction at $I_C = 0.7$ mA. In contrast to the continuous spectral distribution pre-

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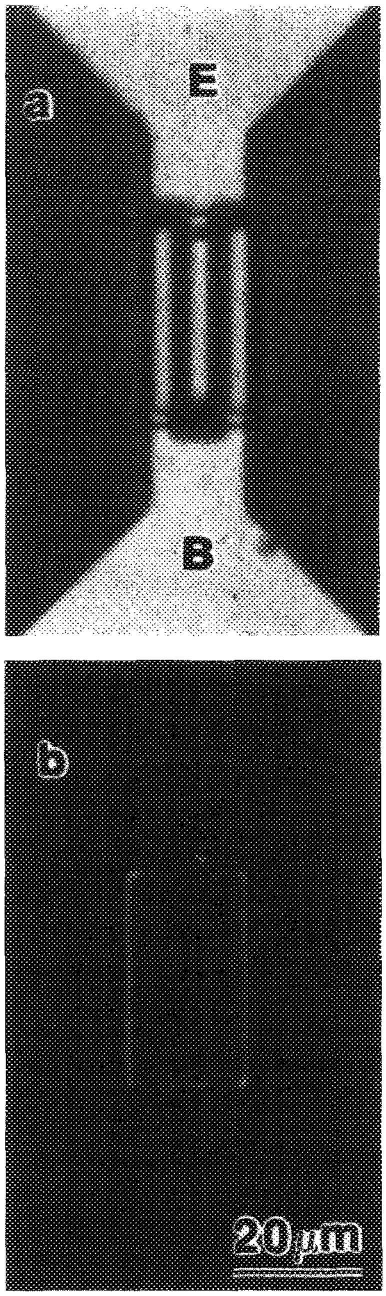

FIG. 1. (a) Top view of the transistor (E and B denote the emitter and base contacts, respectively); (b) light emission from the collector junction at a reverse breakdown current of $I_C = 3.0$ mA.

viously reported by Michel *et al.*[12] for the GaAs *p-n* junction, Fig. 2 shows a distinct transition at 6100 Å (2.03 eV), which corresponds to the observed light emission from the GaAs junction. Additionally, a emission peak is also identified at 8680 Å (1.43 eV), which simply corresponds to the energy gap of GaAs. This band-edge emission we attribute to direct-gap free-carrier recombination and self-absorption.

Before discussing the origin of the observed transitions, we must first examine the process of impact ionization in GaAs, taking into account the real band structure. The threshold energy for carrier impact ionization is the minimum energy required by an energetic carrier to produce an electron-hole pair. In the ionization process, a hot carrier of energy E_i and momentum $\mathbf{k}_i$ makes a transition to the state

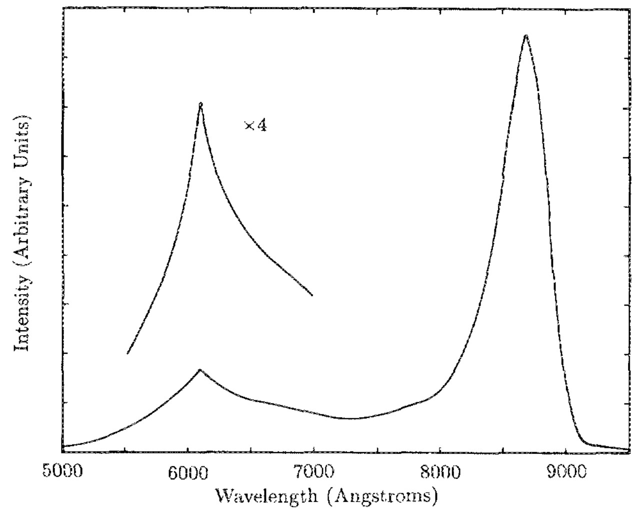

FIG. 2. Emission spectrum of the reverse-biased GaAs base-collector junction at $I_C = 0.7$ mA, showing transition peaks at $h\nu_0 = 1.43$ eV (8680 Å) and $h\nu_1 = 2.03$ eV (6100 Å). The transition peak at 6100 Å is also plotted at ×4 magnification.

E_f, $\mathbf{k}_f$ while promoting an electron in the valence band E_v, $\mathbf{k}$ to the conduction band E_c, $\mathbf{k}'$, with the associated emission or absorption of phonons. Conservation of energy and momentum considerations gives the following relations:

$$E_i(\mathbf{k}_i) = E_f(\mathbf{k}_f) + E_c(\mathbf{k}') - E_v(\mathbf{k}) + \sum_j a_j h\nu_\beta(\mathbf{k}_j), \quad (1)$$

$$\mathbf{k}_i = \mathbf{k}_f + \mathbf{k}' - \mathbf{k} + \sum_j a_j \mathbf{k}_j, \quad (2)$$

where $h\nu_\beta$ is the energy in branch β of a phonon with wave vector $\mathbf{k}_j$ and a_j is any integer including zero (positive a_j corresponds to phonon emission, negative a_j to phonon absorption). It follows from Eqs. (1) and (2), for the case of simple parabolic bands, that the threshold energy for electron-initiated impact ionization is given by

$$E_{ie} = E_g\left(1 + \frac{m_e}{m_e + m_h}\right), \quad (3)$$

where m_e and m_h are the electron and heavy hole effective masses, respectively. Using this formulation, Anderson and Crowell[14] calculated the threshold energy $E_{ie} = 2.1$ eV along the ⟨100⟩ direction of GaAs. Including the nonparabolicity of the energy bands, Hauser[15] calculated $E_{ie} = 1.92$ eV.

In the investigated devices, the electric field is directed along the ⟨100⟩ axis. Presented in Fig. 3 is the band structure of GaAs in the ⟨100⟩ direction, showing electron-hole pair generation and the proposed radiative transitions. As seen from the energy-band diagram, the threshold state for electron-initiated impact ionization in the ⟨100⟩ direction does not occur in the principal conduction band Γ_6–X_6, but instead occurs in the Γ_7–X_7 band, which is separated from the lower conduction band by 0.2 eV at $k/k_{\max} = 0.3$. Under a sufficiently high electric field, the threshold state in the higher conduction band is arrived at by tunneling across the pseudogap, or by means of intervalley scattering.[17,18]

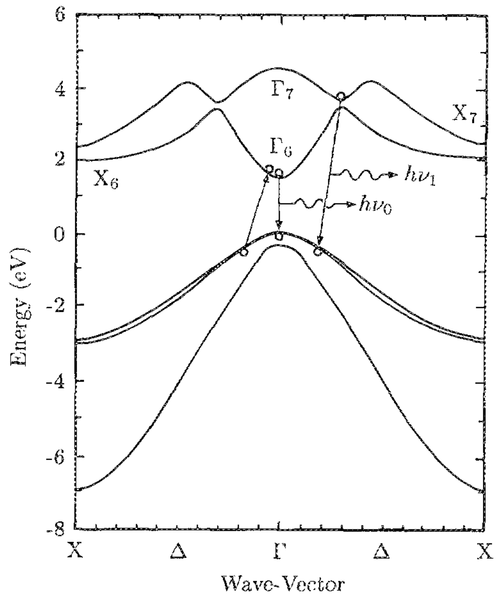

FIG. 3. Energy-band diagram of GaAs along the ⟨100⟩ axis. The electron impact ionization transition from the high-energy Γ_7-X_7 band generates an electron-hole pair and emits the photon $h\nu_1$. (Note that momentum conservation considerations require associated phonon emission for the diagrammed transitions.) Meanwhile, free-carrier recombination at the Γ-valley minima occurs giving the $h\nu_0$ emission.

Given the minimum energy of impact ionization as determined by the threshold state described above, we propose the following equations to describe the transitions observed in the photoemission spectra of Fig. 2. For electron-initiated impact ionization with associated light emission, the energy and momentum conservation relations are

$$E_i(\mathbf{k}_i) - E_i'(\mathbf{k}_i') = E_c(\mathbf{k}') - E_v(\mathbf{k}) + h\nu_1 + \sum_j a_j h\nu_\beta(\mathbf{k}_j), \qquad (4)$$

$$\mathbf{k}_i - \mathbf{k}_i' = \mathbf{k}' - \mathbf{k} + \sum_j a_j \mathbf{k}_j, \qquad (5)$$

where $h\nu_1$ is the energy of the light emission. The energy E_i' and momentum $\mathbf{k}_i'$ describe a hole before recombination with an ionizing electron E_i, $\mathbf{k}_i$. For the minimum energy condition in which the generated electron-hole pairs lie at the conduction and valence band minima, and in which there is no phonon emission or absorption, the photon energy $h\nu_1$ is then just the threshold energy for electron impact ionization. From Fig. 2, the first emission peak at $h\nu_1 = 2.03$ eV agrees with Anderson and Crowell's theoretical value of 2.1 eV.[14] Meanwhile, the emission seen at $h\nu_0 = 1.43$ eV simply corresponds to a free-carrier recombination. The energy conservation relation of this momentum conserving transition is given simply by

$$E_i(\mathbf{k}_i) - E_i'(\mathbf{k}_i') = h\nu_0. \qquad (6)$$

In conclusion, we report the observed emission of light from the base-collector junction of a single heterojunction bipolar transistor. The emission of light from the GaAs junction at breakdown is not observed to subsequently degrade device performance. The photoemission spectrum has been presented for the junction reverse biased to avalanche breakdown. In addition to the expected radiative transition at the direct band gap, we observe a distinct peak at $h\nu_1 = 2.03$ eV. This light emission peak we attribute to recombination of hot electrons corresponding to the threshold energy of electron-initiated impact ionization.

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