ENHANCEMENT OF ELECTRON-INITIATED IMPACT IONIZATION IN SUPERLATTICE-BASED MID- AND LONG-WAVELENGTH INFRARED AVALANCHE PHOTODIODES

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ABSTRACT

We employ a band engineering strategy to enhance electron-initiated impact ionization and suppress hole-initiated impact ionization in Sb-based superlattice infrared avalanche photodiodes. The strategy involved placing a high density of states band at approximately one energy gap above the bottom of the conduction band and simultaneously removing valence bands from the vicinity of one energy gap below the top of the valence band. This gives the electrons a low threshold energy and the holes a high one. Quantitative results are presented for mid-infrared AlAs/InAs/GaInSb/InAs and long-infrared AlAs/InAs/GaInSb/InAs superlattices.

INTRODUCTION

Infrared photodetectors have significant applications in long range, large-capacity, low-noise light wave communication systems and in three-dimensional imaging systems. Avalanche photodiodes (APD) exceptional utility for such applications comes from their high quantum efficiencies, high speeds, low noise, fast rise times, and their sensitivity at low power levels. Since APDs operate under high electric field conditions, the electron and hole impact ionization coefficients are critical to their performance. They determine the excess noise factor (1,2) and the gain bandwidth product (3) of these devices. In an impact ionization process, carriers are multiplied when a hot carrier collides with a valence band electron, causing the electron to be excited across the band gap, creating an electron-hole pair. For an impact ionization process to occur, a hot carrier excited in a high electric field must acquire energy at least equal to the band gap energy.

It is known that resonant enhancement of impact ionization can have its origin in the band structure. APDs composed of Al₉₀.₆Ga₀.₴Sb were predicted to have an enhanced hole to electron impact ionization coefficient ratio due to an equality between Δ, the spin-orbit splitting, and the energy gap E₉. Experimentally this enhancement is observed for low electric fields but not for high fields, a situation that has recently been clarified theoretically (4). However, there is little benefit to exploiting the Δ = E₉ resonance in the band structure of Al₁Ga₁₋ₓSb since many applications require APDs to operate under high electric field conditions. In this paper, we propose the use of Sb-based strained layer superlattices that exhibit a Δ = E₉ like resonance in their band structure. As Mon et al. (5)
described, such a resonance in an AlAs/GaAs superlattice band structure can produce a large difference in the rates of electron- and hole-initiated impact ionization.

The strategy employed here is to engineer the conduction band so that a large density of states exists at an energy one energy gap above the bottom of the conduction band. The superlattice band structure engineered in this fashion will minimize electrons from spreading in energy under high field conditions and will result in an enhanced electron-initiated impact ionization rate. Simultaneously, the valence bands are engineered to have a small density of states an energy gap below the top of the valence band so as to minimize hole-initiated impact ionization. As such, the ratio of electron- to hole-initiated impact ionization rates is large, giving rise to superior APD performance. We show that this procedure works for superlattice APDs in the mid- and long-wavelength infrared (MWIR, and LWIR) spectral regions. Our calculations were unable to identify a superlattice in the short-wavelength spectral region (SWIR) that enhances electron-initiated impact ionization significantly relative to hole-initiated impact ionization. The enhancement of hole-initiated impact ionization with the suppression of electron-initiated impact ionization in Sb-based superlattice APDs is possible in the SWIR, MWIR and LWIR spectral ranges and has been reported in ref. (6).

The purpose of the present work is to accurately evaluate the impact ionization rates of both electrons and holes in superlattice APDs designed to enhance electron-initiated impact ionization. The computational procedure involves obtaining accurate electronic band structures and matrix elements with a 14-band superlattice K-p formalism, and evaluating the impact ionization rates with a Monte Carlo algorithm employing directly these band structures and matrix elements. Details regarding the methods are found in ref. (6).

CALCULATIONS AND RESULTS

In this section, we present results for a MWIR 25Å AlAs/25Å InAs/15Å In$_{0.8}$Ga$_{0.2}$Sb /25Å InAs (5.71 μm cutoff) superlattice and a LWIR 35Å AlAs/40Å InAs/15Å In$_{0.8}$Ga$_{0.2}$Sb/40Å InAs (12.2 μm cutoff) superlattice. In each case, the superlattice unit cell consists of four layers. This adds flexibility to the band engineering in comparison with traditional two-layer superlattices. The superlattices are assumed to be grown on a GaSb substrate and their band structures and impact ionization rates are calculated at 300K.

We present the calculated hole-initiated and electron-initiated impact ionization rates for each of the above superlattices. For hole-initiated impact ionization, the two involved electrons are assumed to be initially in the uppermost spin-split heavy hole band. The initiating hole is permitted to be in the LH$_1$, HH$_1$ or the next highest LH$_2$, HH$_2$ bands (bands are labeled in the figures). The fourth state, initially unoccupied, is in the lowest or the next lowest conduction bands (C$_1$ or C$_2$). For electron initiated impact ionization, the initiating electron is permitted to be in either the lowest or next lowest two conduction bands (C$_1$, C$_2$ or C$_3$). The other electron is in the HH$_1$, HH$_2$, LH$_1$ or LH$_2$ bands. The third and the forth states, initially unoccupied, are taken to be in the lowest conduction band C$_1$. 
Plotting the positions of the most probable carriers involved in the hole-initiated and the electron-initiated impact ionization transitions qualitatively demonstrates the efficacy of the band engineering. For each superlattice, approximately 500 of the most probable hole-initiated and electron-initiated transitions were computed and plotted as a function of the involved carriers' in-plane momentum and superimposed on the band structure. In assessing which transitions are most probable, the occupation probability of the initiating hole was approximated by a Baraff distribution function (7). The following parameters were employed: an electric field of 33 kV/cm; an optical phonon energy of 0.03 eV, the optical phonon energy for pure GaSb (8); and a carrier mean free path of 15 Å, as estimated for GaSb-rich AlGaSb (9).

MWIR 25Å AlAs/25Å InAs/15Å In_{0.8}Ga_{0.2}Sb /25Å InAs Superlattice

The computed band structure of a 25Å AlAs/25Å InAs/15Å In_{0.8}Ga_{0.2}Sb /25Å InAs SL is plotted in Fig. 1. The superlattice has an energy gap of 217 meV at 300K. Several features of the band structure are worth noting. The first is the existence of an $E_G = \Delta$ like resonance in the conduction band. Namely, the two spin-split $C_2$ bands are positioned at energy 229 meV above the conduction band minimum, approximately equal to the energy gap (note that zero of the energy scale is the valence band maximum). The second is the nearly dispersionless character of the $C_2$ conduction band, giving rise to a large density of states. The third is the absence of an $E_G = \Delta$ like resonance in the valence band. The LH$_1$ and HH$_2$ valence bands at zone center are positioned at energies of 368 meV and 495 meV below the valence band maximum, respectively.

The most probable electron-initiated transitions plotted in Fig. 1 demonstrate that the resonance in the conduction band, namely the near equality of the zone-center $C_1$-$C_2$ separation with the band gap, strongly promotes transitions initiated by electrons in the $C_2$. Electrons are represented by solid circles (●) and holes by hollow ones (○). The low threshold energy together with the possibility of transitions with small momentum transfer (and therefore larger transition matrix elements$^6$) result in rapid impact ionization rates.

The most likely hole-initiated transitions plotted in Fig. 2 for the same superlattice are considerably less probable. They involve initiating holes in LH$_1$ with substantially higher threshold energies than the electrons. Thus the band structure of the superlattice appears to fulfill its design goal by providing large electron-initiated impact ionization rates and weak hole initiated ones.

The above qualitative picture is quantitatively verified in Fig. 3. Plotted is the computed impact ionization rate as function of the initiating electron's and hole's energies. The Monte Carlo methodology for computing the integrals results in some scatter, but general trends are clear. Hole-initiated impact ionization is dominated by two closely spaced sharp spikes that are bound above by energies $-495$ meV and $-368$ meV, corresponding to transitions initiated by holes in HH$_2$ and LH$_1$, respectively. Electron initiated impact ionization starts just 229 meV above the conduction band edge, corresponding to a much lower threshold energy than the holes. The near equality of the
zone center C1-C2 splitting and the energy gap permits strong transition amplitudes due to near-vertical transitions.

Fig. 1: The electronic band structure of a 25Å AlAs/25Å InAs/15Å In0.8Ga0.2Sb /25Å InAs MWIR superlattice. The in-plane band structure is plotted to the left (negative wavevectors) and the growth axis structure to the right (positive wavevectors), with the positions of the most probable carriers involved in electron-initiated impact ionization transitions superimposed on the band structure. The filled (open) circles represent electron (hole) states that account for ~ 99% of the total transition rate. The most probable carriers' positions are plotted as a function of in-plane momentum only, hence states not lying on a plotted subband possess a growth direction momentum component.

**LWIR 35Å AlAs/40Å InAs /15Å In0.8Ga0.2Sb/40Å InAs**

Plotted in Fig. 4 is the computed band structure of a LWIR 35Å AlAs/40Å InAs /15Å In0.8Ga0.2Sb/40Å InAs superlattice. The superlattice has an energy gap of 101.9 meV at 300K. The electronic band structure of this superlattice is also designed so that an $E_G = \Delta$ like resonance in the conduction band exists, namely the two spin-split C2 bands are at energy of 139.6 meV relative to the conduction band minimum, approximately equal to the superlattice energy gap. Also, an $E_G = \Delta$ like resonance in the valence band is absent. The zone-center energy separation of the HH1 and LH1 valence bands of 374 meV is much larger than the energy gap.
Fig. 2: The electronic band structure of the same MWIR superlattice with the positions of the most probable hole-initiated impact ionization carriers superimposed.

The most likely electron-initiated transitions plotted in Fig. 4 for the LWIR superlattice shows effects similar to those in the MWIR one, namely that the near equality of the zone-center $C_1$-$C_2$ separation strongly promotes transitions initiated by electrons in $C_2$.

The most likely hole-initiated transitions plotted in Fig. 5 for the LWIR superlattice are less probable. They involve initiating holes in $LH_1$ with a relatively high threshold energy.

Plotted in Fig. 6 is the computed impact ionization rate as function of the initiating electron’s and hole’s energies. Hole-initiated impact ionization is dominated by two closely spaced sharp spikes that are bound above by energies $-483$ meV and $-374$ meV, corresponding to transitions initiated by holes in $HH_2$ and $LH_1$, respectively. Electron initiated impact ionization starts just $140$ meV above the conduction band edge, corresponding to a much lower threshold energy than the holes, and hence more rapid impact ionization.
Fig. 3: Computed impact ionization rate as a function of the initiating hole’s or electron’s energy for the same MWIR superlattice. The threshold energies for various bands and the energy gap of the superlattice are marked.

CONCLUSIONS

Sb-based superlattice avalanche photodiodes in the MWIR and LWIR wavelength ranges have been examined for potential enhancements of electron-initiated impact ionization rates with the simultaneous suppression of hole-initiated rates. Band engineering of the superlattice band structures produces impact ionization resonances in their conduction bands, while preventing similar resonances in the valence bands. As a consequence, the threshold energies for electron-initiated impact ionizations are lower than for hole-initiated ionizations. The band engineering is more effective in the LWIR wavelength range, hence we expect the greatest APD performance enhancements in this range.

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Fig. 4: Same as Fig. 1, but for the LWIR 35Å AlAs/40Å InAs/15Å In$_{0.8}$Ga$_{0.2}$Sb/40Å InAs superlattice.

Fig. 5: Same as Fig. 2, but for the LWIR superlattice.
Fig. 6: Same as Fig. 3, but for the LWIR superlattice.

REFERENCES