Dark current in antimony-based mid-infrared interband cascade infrared photodetectors

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ABSTRACT

The quantum-engineered interband cascade (IC) photodetector is a new type of infrared detectors with many unique and highly desirable features. The multi-stage design allows much flexibility in device optimization for different application environment, such as operation temperature, irradiance level, and possibly high-speed and fast frame-rate application scenarios. Many other distinctive features, such as excellent photo-carrier extraction and photovoltaic (zero-bias) operations, are also very attractive for high performance infrared imaging applications. In this paper, we report our experimental investigation on the dark current mechanisms in mid-wave infrared (MWIR) InAs/GaSb type-II superlattices based IC photodetectors. The electrical performance of MWIR IC detectors with several different designs are presented in detail. The dark current density in the MWIR IC detectors is as low as 4.26×10^{-8} A/cm² (1.44×10^{-3} A/cm²) at -10 mV, with Johnson-limited D^* of 9.11×10^{11} cmHz^{1/2}/W (1.58×10^9 cmHz^{1/2}/W) at 140 K (room temperature) and 3.6 μ m. Our results indicate that the dominating dark current in IC detectors is from tunneling components at lower temperatures, and changes to diffusion current at higher operating temperatures. Furthermore, our effort also shows that the dark current performance in IC devices can be improved substantially by refining the device design and implementations.

PACS keywords:

Semiconductors, III-V: electrical properties of, 73.61.Ey; Structure of superlattices, 68.65.Cd; Quantum wells devices, 85.35.Be

The InAs/GaSb type-II superlattice (T2-SL) based interband cascade (IC) detectors are emerging as a new type of high-performance infrared (IR) photodetectors [1-5]. They fully take advantage of the great versatility in energy-band alignment for antimony-based III-V semiconductor materials, and ultra-fast carrier relaxation channels are implemented into the device operation [2-6]. Many highly desirable features and unique device characteristics can be realized in IC photodetectors, making them very attractive to a wide range of applications for IR detection and imaging, particularly for these applications with strong demand on SWaP (small size, weight, and power) and high operating temperatures (HOT) [2-7]. We have demonstrated single-pixel mid-IR IC photodetectors with very low dark current [4] and operation temperatures up to 450 K [5]. Very recently, the first IC focal plane array (FPA) was demonstrated in the mid-IR [5]. The 320×256 FPA was hybridized with a commercial standard read-out circuit. Even with the 0.7- μm total absorber and non-optimum fabrication, the mid-IR IC FPA was operational above 180 K, with noise equivalent temperature difference (NEDT) of 28 mK at 120 K [5]. These results show the great potential of IC detectors for high performance and HOT applications. To further explore this technology, it's important to understand the operation principles and underlying physics related to such a relatively complicated device structure. The signal performance in IC detectors has been investigated experimentally, and the basic operation principles are relatively well understood [2-3]. However, the dark current mechanisms in these quantum-engineered IC detectors, with the multiple-stage/junction design, are not yet clear. Some speculate that, similar to junction-type photodiodes, the fundamental limit in the noise performance for IC detectors could be bulk processes such as Shockley-Read-Hall and Auger processes [8]. However, with their distinctive architectures, and multiple types of carrier transport processes [3-4] combined, the dark current mechanisms in IC detectors are quite complicated, and could be governed by different mechanisms. In this paper, we present our experimental investigations on the dark current of mid-wave IR (MWIR) IC photodetectors, with various barrier and absorber designs, over a wide operating temperature range.

Typically an IC detector is consisting of multiple stages that are electrically connected in series, via interband tunneling facilitated by the type-II broken-gap alignment. In each stage, there are 3 different regions – an electron barrier (eB), a relatively thin InAs/GaSb T2-SL absorber, and a specially designed electron relaxation region [which also serves as a hole barrier (hB) to the absorber]. The band structure and basic operation principle of IC detectors are as shown in Fig. 1: the incoming photons are absorbed in the T2-SL absorbers, creating photon-excited electrons; because the eB is placed adjacent to the left of this absorber region, the electrons can only move toward the right; the electrons will then travel through an ultra-fast electron relaxation path – via longitudinal optical (LO) photon assist intersubband relaxation at *sub-ps* level, in the electron relaxation region; and finally tunneling into the valence band of the next

stage. Detailed description of the device operation, characteristics, and implementations could be found in reference 2-4.

The samples are grown on Zn-doped 2" (001) GaSb substrates by using a Veeco Gen-10 solid-source molecular beam epitaxy (MBE) system, equipped with group-III SUMO cells and group-V valved crackers. The growth rates of the group-III sources are determined by reflection high energy electron diffraction (RHEED) oscillation, and are then verified by the SL periods as determined by the separation of the x-ray diffraction (XRD) satellite peaks in the XRD rocking curves. The V/III ratios are tuned for optimum crystal and optical quality, as confirmed by XRD and photoluminescence measurements. The epi-ready substrates are first loaded into the MBE chamber, and then heated up to oxide desorption temperature, which is verified by a streaky RHEED pattern. The epi-structure starts with a 0.3 μm *p*-type GaSb buffer layer, followed by a 5-stage interband cascade structure, and is finalized by a *n*-type InAs top contact layer. In sample-set A, the absorber region in each stage is composed of 30-periods (~ 140 nm) of a non-intentionally doped (N.I.D.) 6-ML InAs/9-ML GaSb (ML stands for monolayer) T2-SL, while for sample-set B, the absorber is composed of 30 period of 7-ML InAs/8-ML GaSb T2-SL. The eB region consists of GaSb/AlSb MQWs, with estimated barrier height of ~ 0.68 eV for sample-set A, and ~ 0.72 eV for sample-set B. The hB region is composed of 6-8 pairs of InAs/Al(In)Sb QWs, forming an energy-staircase in the conduction band, with the upper-most energy state aligned with the mini-band in the conduction band of the T2-SL absorber, and the lowest energy ladder close to the hole energy level in the valence band of the eB in the next stage. After growth, the epitaxial wafers are characterized by X-ray diffraction (XRD) to monitor the crystal quality and layer thicknesses in their structures. For sample-set A, the estimated InAs/GaSb SL periods are about 47.7 $\text{\AA}$, which is about 2.1% thicker than our design, and the full width half maxima (FWHM) of the satellite peaks are around 30 arc-seconds. The overall strain of the epi-layers is estimated to be less than 50 arc-seconds. For sample-set B, the T2-SL period is about 47.5 $\text{\AA}$, and the FWHM is around 26 arc-seconds, which may indicate a better interface quality in sample-set B. The samples are then processed into deep-etched mesa-type photodiodes using standard contact UV lithography and wet-chemical etching. The circular mesa-size ranges from 25 to 400 μm in diameter. A 200-nm-thick SiN_x film is deposited for sidewall passivation and electrical isolation. Top and bottom contacts are then formed by e-beam evaporated Ti/Au. No anti-reflectance (AR) coating is applied to the top of the mesas. Devices are mounted on ceramic leadless chip carriers and then mounted in a cryostat to characterize their optical and electrical performances. The dark current is measured with a HP 4145B source-measurement unit. The response spectra are collected by a Nicolet 6700 Fourier transform IR (FTIR) spectrometer using a broad-band IR glow-bar source.

These mid-IR IC photodetectors are operational well above 400 K, with cut-off wavelength of ~ 4.9 μm at 300 K. The responsivity is around 0.16 A/W at 4 μm and room temperature. Given the fact that the photoconductive gain in IC detectors is inversely proportional to the number of stages, the absorption quantum efficiency is estimated to be around 25%. The responsivity increases monotonically with operation temperature (up to 420 K), due to the increased absorption coefficient in T2-SL at higher temperatures. As we know, the carrier lifetime in InAs/GaSb T2-SLs is relatively short, especially at higher temperatures. Therefore, the superior optical performance at high temperature also verifies the very efficient photo-carrier extraction in the IC photodetectors. For sample-set B, the zero-bias response is above 85% of its saturation [7]. This is quite important for obtaining high performance IR detectors [4], since the major dark current components scale with the operation bias, as required to “turn-on” the conventional junction and/or barrier-based IR photodetectors. It’s should be noted that a moderate responsivity reported here does not mean that the IC photodetector has inferior overall performance. In fact, the attainable signal-to-noise ratio (SNR) in IC detectors could be higher compared with conventional photodetectors [4-5, 7]. For applications where higher quantum efficiency is required, IC detectors with thicker absorber designs can be adopted.

Figure 2 shows the dark current characteristics of 5-stage mid-IR IC photodetectors in sample-set A, with different electron barrier thicknesses. The absorber and hB regions for sample-set A remain the same, while the AlSb/GaSb eB thicknesses in sample A1, A2, and A3 are 17 nm, 33 nm, and 45 nm, respectively. As one can see from Fig. 2, the dark current in IC detectors with thicker eB is much lower below room temperatures. The difference in dark current is more obvious (for example, over 10 times at -1 V and 120 K) at lower temperature and high bias conditions. This indicates that electron tunneling current between stages is the dominating factor to the device dark current. At above room temperature, the dark current in these IC devices converges, indicating that the dark current is more intrinsic to the absorber region, which could be dominated by either diffusion or generation processes. In our IC detector designs, due to the existence of ultra-fast carrier relaxation path and relatively thin absorbers, the electrons (thermal-carrier) are expected to be quickly extracted from the absorber, and therefore dark current contribution from recombination process is expected to be greatly suppressed. The dark current density for these mid-IR IC devices is as low as 1.01×10^{-7} A/cm² at 150 K and -5 mV, which is better than that extrapolated from MCT rule07 [4, 9].

To investigate the temperature dependence of the electrical performance, the dark current density (solid line) and R_0A (dot line) of IC devices from sample-set A is shown in an Arrhenius plot (Figure 3). As we can see in Fig. 3, the difference among sample-set A is minimum at above room temperature. The activation energy extracted from the dark current characteristics at higher temperatures is around 0.299

eV, which is slightly higher than the bandgap. This indicates the dark current is mainly contributed from the diffusion component. The R_0A characteristics of the IC detectors show similar temperature dependence. However, the difference in R_0A between IC detectors with different absorber designs at lower temperatures is up to 50 times, indicating an efficient dark current suppression with a thicker electron barrier design.

Based on our experimental investigation results from sample-set A, the dark current in the mid-IR IC detectors at lower temperatures, is limited by the tunneling current through the electron barrier; while at higher temperatures, the diffusion component becomes dominate. To further validate these conclusions, the electrical performance of sample-set B with different absorber designs is also investigated in detail. Sample B1 is very similar to A3 in design, except that a 30 period of 7-ML-InAs/8-ML-GaSb T2-SL absorber is used. The eB height (with respect to the conduction band-edge of T2-SL absorber) in sample B1 is slightly higher than in sample-set A. Sample B2 is identical to sample B1 except that 60-period 7-ML-InAs/8-ML-GaSb SL absorbers are adopted. Figure 4 shows the comprehensive comparison of dark current characteristics between sample B1 (bold lines) and A3 (slim lines) under various temperatures. As we can see, the dark current in sample B1 (under reverse bias up to 1.2 V) improved over the whole temperature range, as compared to sample A3. The rectification behavior for sample B1 at forward bias is also improved, which shows improved overall carrier transport properties. The dark current in sample B1 at lower temperatures (below 200 K) and higher reverse biases shows some significant increase, indicating the increased tunneling component due to the higher electrical field in the devices. Nonetheless, the dark current of device B1 is much lower as compared to device A3, under small reverse bias (as well as under zero-bias, which is of particular interest due the photovoltaic operation nature of IC detectors). The dark current density of device B1 is as low as 1.09×10^{-9} A/cm² at -10 mV and 100 K, which is shows nearly 3-times reduction compared to device A3 (under identical operation conditions). The reduced dark current at lower temperatures is attributed to the slightly higher eB height and slightly p-doped absorber, which would significantly reduce the available electron concentration in the conduction band. At room temperature, the dark current density of sample B1 is 1.85×10^{-3} A/cm² at -10 mV, which is half compared to device A3. The improved dark current could be attributed to the reduced electron concentration in T2-SL resulted from the slightly p-doped absorbers in sample B1.

As discussed earlier, the dark current in IC devices at higher temperatures could be associated with the diffusion component, rather than the generation process. This is also verified by the dark current behavior in sample-set B. Figure 5 shows Arrhenius plot of the electrical performance in MWIR IC device B1, B2, and A3. As we could see, sample B1 and B2 show improvement in electrical performance over device A3. The dark current density in device B2 is as low as 3.44×10^{-8} A/cm² at 140 K and -10 mV,

which is ~25% lower compared to device B1 and 40% lower compared with device A3. The R_0A for sample B2 at 140 K is $4.55 \times 10^5 \Omega \text{cm}^2$, which is 1.6 and 2.8 times higher compared with device B1 and A3, respectively. The activation energy ($E_A = 0.293 \text{ eV}$) of sample-set B extracted from the dark current characteristics at higher temperatures is also close to the bandgap of the T2-SL absorber, indicating again that the dark current at higher temperatures is mainly due to the diffusion component. It's worth noticing that the dark current in sample B2 is actually lower compared to B1, which again implies that the dominating dark current mechanism at lower temperatures is not from generation-recombination component. Our speculation is that the dark current at lower temperature in these IC detectors with enhanced electron barrier designs [3-4] could be due to band-to-band or trap-assist tunneling processes. At higher temperatures, the electrical performance between sample B1 and B2 again start to converge, which confirms that the dark current is dominated by diffusion process (as one would see some significant difference if the dark current is dominated by SRH generation component). Because of the improved zero-bias optical properties as well as the superior electrical performances, the MWIR IC detector B1 has demonstrated a Johnson-limited D^* up to $9.11 \times 10^{11} \text{ cmHz}^{1/2}/\text{W}$ at 140 K, and $1.58 \times 10^9 \text{ cmHz}^{1/2}/\text{W}$ at room temperature, respectively.

In summary, the electrical properties of T2-SL based MWIR interband cascade photodetectors have been extensively investigated. Unlike the PIN diode and barrier detectors, our experimental investigation on IC detectors with different electron barriers and absorber designs indicate that the dark current in IC detectors is limited by tunneling processes at lower temperatures, and is determined by diffusion current at above room temperatures. Our investigation shed light on the understanding of quantum-engineered IC photodetector, as well as similar multi-stage/junction devices, and provides guidelines for the IC detector design and optimization.

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Figure captions

Fig. 1 Band structure diagram and operation principle of Interband Cascade photodetectors. Two cascade stages in IC detector are included, and the relevant envelop wave-functions and their respective energy levels are shown. The incoming photons are absorbed in the InAs/GaSb T2-SL absorbers, generating electron-hole pairs. The electrons will diffuse into the electron relaxation region, and then effectively transport into the valence band of the next stage, through fast LO-phonon assist intraband relaxation and interband tunneling.

Fig. 2 Dark current characteristics of single-pixel MWIR IC detectors with different eB thicknesses (sample-set A) at various operating temperatures.

Fig. 3 Arrhenius plot of the electrical performance in single-pixel MWIR IC detectors (from sample-set A) with different electron barrier designs.

Fig. 4 Comparison of dark current characteristics of MWIR IC detectors with different absorber designs. The slim lines are the dark current of device A3, and bold lines are device B1.

Fig. 5 Arrhenius plot of the noise performances for MWIR IC detectors with different absorber designs. The bold lines represent the dark current density behavior at -50 mV, and the slim lines are the R_nA characteristics.

Figures

Fig. 1

Fig. 2

Fig. 3

Fig. 4

Fig. 5