Dark current mechanisms and spectral response of SiO₂-passivated photodiodes based on InAs/GaSb superlattice

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ABSTRACT

The electrical performance of SiO₂ passivated type-II superlattice double heterostructure photodiodes is demonstrated. Compared to unpassivated samples, a dark current of 4.009×10^{-5} A/cm² and the corresponding differential resistance-area of 165.82 Ω.cm² at zero bias voltage are achieved at 77 K. The temperature-dependence and bias-dependence of the dark current are studied experimentally. According to fitting results, the existence of the SiO₂ passivated layer alters the band bending at the interface, which influence the generation-recombination and trap-assisted tunneling current and then it present that the total dark current is reduced by introducing the SiO₂ passivation technology. At 77 K, the corresponding spectral responsivity and detectivity of the samples are measured at a bias voltage of -50 mV and the 100% cutoff wavelength is determined to be 10.6 μm, which is fitted well with the simulation results of temperature dependence of experimental data.

Keywords: InAs/GaSb; Passivation; Dark current; Mechanism.

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1. Introduction

Since the idea of Type-II InAs/GaSb superlattice (T2SL) was first proposed by Sai-Halasz and Esaki in the 1970s^[1]. Due to its outstanding fundamental properties, T2SL has experienced an incredible improvement in material quality, device structure design and device fabrication process over past decades, especially for infrared detection and imaging technology^[2]. Compare to the Mercury Cadmium Telluride (MCT) material system, the effective mass in T2SL is relatively large, which is a major meaningful property to reduce the dark current of long and very long wavelength detectors. While the detection region extend to longer wavelength with a small energy gap, the dark current performance of device becomes more sensitive not only to the bulk properties, but also to the surface leakage of the exposed sidewall, and the hardly-cancelled contribution part is still limited by surface leakage due to the absence of an effective passivation technique that can protect mesas from sidewall leakage and it becomes more severe as device size scale down for higher resolution imaging system.

Surface leakage generally originates from the abrupt termination of the periodic structure, contamination from processing, and fixed charges within the passivation layer, which can generate band bending on exposed-sidewalls. This band bending causes electron accumulation or type inversion at sidewall surfaces, resulting in a conduction channel beneath the surface^[3-5]. So far, various improvements^[6-13] have been made to understand sidewall surface physics and suppress surface leakage in the long wavelength infrared photodiodes. SiO₂ passivation is still the dominant and most

suitable passivation technique for T2SL application. However, owing to the complexity of the device's surface states, the distribution of the surface leakage current is hard to be applied sufficient analysis. Current-voltage measurement is an efficient way to verify the quality of a photodiode, and allows us to extract the zero-bias resistance area product (R_0A) and to identify the dark current mechanism. By comparing the simulation results with experimental data, change of the dark current mechanism could be predicted.

In this paper, the current-voltage characterization of unpassivated and SiO_2 passivated samples are studied. The temperature-dependence and bias-dependence of the dark currents are studied experimentally, which is also correlated to the theory. A hypothesis is proposed to interpret to the surface leakage of the sidewalls of the unpassivated and passivated samples. The corresponding dark current component distribution of unpassivated and passivated samples is disclosed, which is meaningful to improve device performances.

2. Material and methods

The samples presented in this work were grown on a GaSb substrate by Riber C21T solid source molecular beam epitaxy (MBE) system. The design used was a heterostructure based p-i-n structure. The corresponding schematic representation of the grown structure and the band structure of the heterostructure is shown in Figure.1. The following structure consisted of a 380-nm-thick GaSb: Be buffer ($p^+ \sim 10^{18} \text{ cm}^{-3}$), followed by a 500-nm-thick InAs/GaSb:Be ($p^+ \sim 10^{18} \text{ cm}^{-3}$) superlattice, a 2144-nm-thick InAs/GaSb active region, a 500-nm-thick InAs:Si ($n^+ \sim 10^{18} \text{ cm}^{-3}$)

/GaSb region and topped with a thin InAs capping layer. The superlattice design for the absorption region used 13 monolayers (MLs) of InAs and 7 MLs of GaSb in one period and this region was unintentionally doped. The superlattice design for the p^+ - and n^+ -type region used 8 MLs of InAs and 8 MLs of GaSb in one period by inserting an InSb layer of thickness 1 ML. The concentration of the doped p^+ - and n^+ -type contacts are at least two orders of magnitude higher than the active region. The primary absorption region presents a band gap around 115 meV, while the band gap of the p^+ and n^+ contacts superlattice regions is around 250 meV. This double heterostructure^[14] that can suppress the surface leakage at the interface between the active region and the p or n contact. Therefore, for simplicity, the discussion is focused on the active region while the influence of the p^+ - and n^+ -type contacts is assumed to be less pronounced than the active region. The single-pixel devices with diameters varying from 100 to 400 μm were fabricated with the same processing procedures^[15, 16]. Some samples were left unpassivated for reference, and others were passivated with SiO_2 dielectric layer. For the measurements, the diodes were wire-bonded and then loaded into a cryostat for characterization. All results reported in this paper were obtained for photodiodes without antireflective (AR) coating.

The crystalline quality of samples was characterized by double crystal X-ray rocking curve system, all measurements were performed around GaSb (004) symmetry axis with 0.0005° precision by using Cu $K\alpha_1$ radiation ($\lambda = 0.15406 \text{ nm}$). Atomic force microscopy technology was used to investigate the surface roughness. The cutoff wavelength of fabricated detectors was determined through spectral response

measurements performed using a Nicolet 670 Fourier transform infrared (FTIR) spectrometer with a glow-bar black body source.

3. Results and discussion

A typical X-ray rocking curve diffraction pattern obtained from the samples is shown in Figure. 2. The well-resolved SL diffraction peaks up to the tenth order are observed and it is found that the full width half maximum (FWHM) of the zeroth order peak is 30 arcsec. The mismatch between the zeroth peak and GaSb substrates ($\Delta a/a$) is about 9.01×10^{-4} . The corresponding atomic force microscopy (AFM) exhibits uniform atomic steps with Root-Mean-Square (RMS) roughness of 2.1 Å at $10 \times 10 \mu\text{m}$ scan, and these parameters indicate high crystalline quality.

The SiO_2 passivated samples with diameter 100 μm are used to study the temperature-dependence of the dark current. Shown in the Figure. 3 are the values of the dark current densities and the differential resistance at temperatures ranging from 77 K to 300 K. A dark current of $4.009 \times 10^{-5} \text{ A/cm}^2$ and the corresponding differential resistance-area of $165.82 \Omega \cdot \text{cm}^2$ at zero bias voltage are achieved at 77 K, which is found to have a 3 times reduction in current density as compared to 300 K.

The total dark current contains bulk and surface-limited components. The bulk-limited dark current in a given device is the sum of the diffusion current, generation-recombination (GR) and tunneling current. The relation between the applied voltage, V , and the diffusion current density^[17] is given by

$$J_{diff}(V) = q \left[\frac{n_i^2 D_e}{N_A L_e} + \frac{n_i^2 D_h}{N_D L_h} \right] \left(\exp \frac{qV}{kT} - 1 \right) \quad (1)$$

Where q is the electron charge, k is the Boltzmann constant, N_A and N_D are the p - and n -type doping concentrations, respectively; L_e , L_h and D_e , D_h is the electron and hole diffusion lengths and diffusion coefficients.

The GR current is due to various GR processes taking place inside the diode, such as Shockley-Read-Hall (SRH). When the photodiode operates at small reverse bias, the dominant SRH GR current density^[18] under reverse-bias voltage values, that are less than V_B by several kT/q , is derived as

$$J_{GR} = \frac{qn_i W}{\sqrt{\tau_n \tau_p}} \frac{\sinh(-qV/2kT)}{q(V_B - V)/2kT} f(V), \text{ with } f(V) = \int_0^\infty \frac{dx}{x^2 + 2e^{-qV/2kT} x + 1} \quad (2)$$

Where W is the depletion width which depends on the applied bias V and the built-in potential V_B , n_i is the intrinsic carrier concentration, τ_n, τ_p are the lifetimes for electrons and holes. The intrinsic carrier concentration is calculated in the parabolic energy band approximation from the following relation:

$$n_i = 2[2\pi k/h^2]^{3/2} (m_e m_h)^{3/4} T^{3/2} \exp(-E_g/2kT) \quad (3)$$

m_0 is the free electron mass. We used $m_e = 0.03m_0$ and $m_h = 0.4m_0$.

For the tunneling current, while photodiodes normally operate in a lower bias region, and the band-to-band (BTB) tunneling current isn't the dominant contribution part. Hence, the BTB tunneling current is reasonably neglected in this paper and the contribution of the trap assisted tunneling (TAT) current^[19] can be expressed as follows:

$$J_{TAT} = \frac{q^2 m_T V M^2 N_T}{8\pi h^3 (E_g - E_t)} \times \exp\left\{-\frac{4(2m_e)^{1/2} (E_g - E_t)^{3/2}}{[3q h F(V)]}\right\} \quad (4)$$

Where m_T is the reduced tunneling effective mass equal to $0.02m_0$, E_g is the effective

bandgap of SLs material, h is Planck's constant, $F(V)$ is the electric field strength across the depletion region, E_t is the location of trap levels below the effective conduction band edge, and N_T is effective activated trap density. M^2 is the matrix element associated with the trap potential, and $M^2 = 1 \times 10^{-23} \text{ eV}^2 \text{ cm}^3$ is used.

Based on the above-mentioned current distribution, the dominant contribution of dark currents in photodiodes varies with temperatures. At high temperature, diffusion has a great dependence on temperatures and is affected by temperatures mostly via the factor n_i^2 , which is proportional to $\exp(-qE_g/kT)$ as depicted in Eq.(1). When the temperature is lowered, the influence of diffusion current decreases gradually and gets smaller, where the GR current becomes dominant. It exhibits linear with a slope of $qE_g/2k$ as depicted in Eq. (2).

Shown in Figure 4 (a) is the temperature dependence of experimental and theoretical fitting under 50 mV reverse bias for SiO_2 passivated photodiodes. The dark current density can be generally written as $J_{Dark} = J_0 \exp\left(-\frac{\Delta E_{act}}{kT}\right)$, where ΔE_{act} is the activation energy. The active energy is calculated by taking the logarithm for the two sides of this formula. Two regimes can be clearly observed above and below 150 K. At above 150 K, the diode exhibits diffusion-limited behavior and the slope also gives an activation energy of 115 meV, which is approximately equal to the band gap E_g of the absorber region. When the temperature range was from 100 K to 150 K, the GR-limited mechanism can fit it well, thus the fitting data of activation energy is only about 3.3 meV, which means that the measurement result is out of accordance with the fact that the GR activation energy approximately $E_g/2$. The origin of the

mechanism is not clear and may be due to tunneling or surface effects. Accordingly, when the temperatures were even further decreased, the GR current would present to be smaller, and it is necessary to take the other mechanisms into account to understand the performance of the photodiodes. In order to identify each current component, analysis of the each dark current mechanism was performed on current voltage curves recorded. Figure.4 (b) shows a comparison of the dark current between the unpassivated and passivated sample at 77 K. The introduction of passivation technology fulfilled the dark current density by 3 times reduction under reverse bias voltage. The dark current of the SiO₂-passivated sample is also fitted using formula (1), (2) and (4). The bulk-limited dark current contains the diffusion, GR and TAT tunneling current. According to the fitting curves, it shows that the diffusion current is not the dominant mechanism. The model with GR mechanism describes the dark current at low applied bias, however, it is hard to explain the value of the dark current at high bias. The simulation of the TAT component was also plotted. As the reverse bias gets bigger, the GR current and TAT current are all increasing and work together, which also become the main contributing mechanism to the total dark currents. Meanwhile, the results show that the bulk-limited data match with the experimental data well at low bias voltage region, but at higher bias voltage, there is some difference. Compared to passivated samples, this difference presents to be more obvious for unpassivated samples, and so it is worth to be explored to explain the difference between bulk-limited and experimental data.

In order to obtain the amount of surface leakage, the size-dependent R_0A is studied. A model for the dependence of R_0A on P/A was first developed to model sidewall leakage in HgCdTe detectors ^[20]. The same model can be applied to this fitting. In Figure 5 (a) shows the inverse dynamical impedance area $(R_0A)^{-1}$ vs Perimeter over Area (P/A) ratio for various sizes of diodes. The R_0A contribution is written as: $(R_0A)^{-1} = 1/a + (1/b) \times (P/A)$, a is the bulk R_0A contribution and b is the surface resistivity. According to the fitting results, the parameter a , which is equal to $166.389 \Omega \cdot \text{cm}^2$ and the related parameter b is equal to $2.6528 \times 10^4 \Omega \cdot \text{cm}$. From the fitting curve, the R_0A value of the surface with the diameter $100 \mu\text{m}$ is calculated to be $1.88 \Omega \cdot \text{cm}^2$. This plot presents the dark current of this SiO_2 passivated sample comes mostly from the bulk. In Figure.5 (b) shows the difference between experimental data and bulk-limited data under the reverse bias region. The bulk-limited contribution contains diffusion, GR and TAT as explained in Figure.4 (b). So this difference data is actually surface leakage. The surface leakage presented a little contribution to the total dark currents at low applied bias, while the bias becomes bigger, the surface leakage increases apparently.

In an effort to predict the surface contribution of the unpassivated samples, it is assumed that bulk-limited part is uniform to the passivated sample as fitting in Figure.4 (b). In Figure.6 (a), at 77 K, the total dark current was decomposed into bulk-limited and surface-limited part. Compared with the passivated samples, the experimental data of the unpassivated sample is mostly dominated by the surface leakage mechanism under reverse bias regime and the bulk-limited component is not

considered as the main contribution. So the difference of these two surface leakage current fitting result is caused by sidewall passivation. In another way, assuming that surface-limited part is uniform to the passivated sample as fitting in the Figure. 5(b), we can also predict the bulk-limited contribution of the unpassivated samples. The detail component of dark current is disclosed. According to the fitting results shown in Figure. 6(b), the diffusion and the surface-limited weren't the dominant contributing mechanism. The GR and TAT become the most contribution to the total dark current. And it is valuable to note that the transition point from GR to TAT mechanism, which shows that the GR will reduce with the increasing bias voltage and it is consistent with the reduced space region width, resulting apparent increase of the TAT current.

In p-i-n structure, the double heteostructures can effectively prevent the inversion of higher band gap p and n superlattice contact regions, thus it can be recognized that the surface leakage current mainly comes from the primary active absorption region. As for the other leakage current originating from the device's surface, which is covered by InAs capping layer and this part can be ignored. So the main part of the surface leakage is assumed to be from the active region of mesa-sidewalls. The presence of surface leakage can be explained using the surface potential theory. With a nonzero surface potential at the sidewall interface, band-bending occurs due to the Fermi level position and this results in accumulation/inversion of majority carriers that then can create conductive leakage channels parallel to the surface ^[5]. In fact, the important reasons for the nonzero surface potential are the dangling bonds and undulation effects presented on the device sidewalls. In addition to the surface potential

modification native oxides and contaminants also contribute to dark current by creating additional interface states. Interface states located within band-gap alleviate the carrier tunneling, inducing surface recombination and contributing to trap-assisted tunneling dark current ^[21]. Thus the existence of the SiO₂ passivated layer can act as a barrier layer or protection layer to the surface, and alters the band bending at the interface, which influences the GR and TAT value. For the unpassivated samples, absence of effective surface treatment, the exposed sidewalls show the strong band bending. This band bending provokes severely accumulation of charges, further shorting the *p-n* junctions. It can also modify the surface potential and create trap levels in the energy gap, increasing the dark current.

To show the effects of the SiO₂-passivation on the photoelectric properties, the spectral responsivity and detectivity have been measured. As shown in Figure. 7(a), the corresponding spectral response of the passivated and unpassivated samples was measured at 77 K, respectively, and the 100% cutoff wavelength is determined to be 10.6 μm . Compared with unpassivated samples, the SiO₂-passivated samples have a similar spectral response, thus within 3 to 5 μm wavelength ranges, and there had been a significant increase. Figure. 7(b) shows the corresponding detectivity of these samples in the whole spectral region at -50 mV bias. It is obviously found that both of the spectral response intensity and detectivity benefited from the reduction of the dark current, which presented the dark current is effectively suppressed by the introduction of SiO₂-passivation technology.

4. Conclusions

The unpassivated and SiO₂ passivated type-II InAs/GaSb superlattice long wavelength photodiodes are disclosed. The temperature-dependence and bias-dependence of the photodiodes dark current is studied experimentally. Even the dominant dark current of the passivated sample is proved to bulk-limited, but the surface leakage mechanism can't be ignored. The existence of the SiO₂ passivated layer alters the band bending at the interface, which influence the GR and TAT value and the total dark current is reduced by introducing the SiO₂ passivation technology. It is meaningful to investigate the detail component of the dark current, which is good for predicting the device's electrical performance and provide a way to make it progress.

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Figure captions

Figure. 1 The schematic representation of the grown structure and the band structure of the heterostructure.

Figure. 2 High resolution X-ray diffraction of a typical superlattice design, and the diffraction peaks exhibit narrow FWHM up to high ordered satellite. The inset picture shows the corresponding AFM surface with RMS roughness of 2.1 Å.

Figure. 3(a) Dark current density-voltage of the SiO₂-passivated samples with diameter 100 μm at different temperatures ranging from 77 K to 300 K, and (b) the corresponding differential resistance-area value.

Figure. 4(a) Temperature dependent dark current densities (-50 mV) for passivated samples. The diffusion and GR limited regimes are reported. (b) Total modeled and simulated current densities considering diffusion, GR and TAT for the passivated sample investigated at 77 K. The dark current of the passivated sample is also compared with unpassivated sample and the surface leakage current is significantly reduced.

Figure. 5(a) Variation of the differential resistance at zero bias as a function of the perimeter over area of the passivated samples. The red line is a linear fit of the data points. (b) Calculation of the surface leakage current as a function of the applied bias for passivated samples at 77 K. The total modeled data accurately describe the experimental dark current for the whole range reverse biases (0 ~ 0.5 V) considered. The bulk-limited contribution is also investigated.

Figure. 6(a) Assuming that bulk-limited part is uniform to the passivated sample as fitting in Figure.5(b) The total dark current was decomposed into bulk-limited and surface-limited part at 77 K. (b) Assuming that the surface-limited part is uniform to the passivated sample as fitting in Figure.4 (b), the detail component of the unpassivated sample is disclosed at 77 K.

Figure. 7 The spectral responsivity and detectivity of the passivated and unpassivated measured at bias voltage of -50 mV at 77 K and the 100% cutoff wavelength is determined to be 10.6 μm .