

Investigation of the lower temperature SiO₂ surface passivation technology on InAs/GaSb superlattice detectors

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Abstract. We report on the investigation of effective SiO₂ passivated layer deposited at low temperatures. Comparison with the unpassivated photodiodes, at 77 K, the dark current density is reduced by one order of magnitude is achieved by introducing SiO₂-passivated layer deposition technology at a lower temperature of 75 °C. The temperature-dependence and bias-dependence of the dark current are studied experimentally and correlated to the theory, and then the contribution of each dark current mechanism is also identified.

Introduction

InAs/GaSb Type-II superlattices (T2SL) have been a promising alternative to replace the leading Mercury-Cadmium-Telluride (MCT) system for infrared detection and imaging. Due to its great advantage for band structure engineering, which results in greater flexibility in controlling the band gap [1], suppression of Auger recombination [2], and design of novel device architectures [3-5], this material system has demonstrated rapid progress. However, the performance of T2SL photodetectors, especially in long-wavelength infrared region, is still limited by the high dark current. The identification of each individual dark current mechanism, such as surface leakage, diffusion, generation-recombination (GR) and trap-assisted tunneling (TAT) current, is very important for the understanding of the pin photodiode and then to improve SL device electrical and optical performances. Among these current mechanisms, the minimal of surface leakage is crucial to be resolved for reducing the total dark current and obtaining the high resolution imaging system.

Generally, surface leakage is believed to originate from the abrupt termination of the periodic crystalline structure, contamination from processing, and fixed charges within the passivation layer, which can generate band bending on mesa-sidewalls, this band bending causes electron accumulation or type inversion at sidewall surfaces, resulting in a conduction channel along sidewalls [6, 7]. Several surface passivation attempts have been proposed to minimize the dark currents, thereinto, SiO₂ passivation, which can be compatible with standard semiconductor fabrication procedures, is still the dominant and most suitable passivation technique for T2SL application. However, SiO₂ film deposition usually utilizes a plasma enhanced chemical vapor deposition process conducted at high temperatures and exposure of SLs materials to high temperatures could degrade the overall device performance [6]. So special care needs to be taken to develop a low-temperature process of SiO₂ deposition technology to prevent SLs period intermixing and improve the electrical performance.

In this paper, we introduce a low-temperature inductively coupled plasma chemical vapor deposition technology (ICPCVD) and the SiO₂-passivated layer was performed at a temperature of 75 °C to reduce the surface leakage current. The temperature-dependence and bias-dependence of the passivated and unpassivated photodiodes dark current is studied experimentally and correlated to the theory.

Materials and methods

Samples presented in this paper have been grown by Riber C21T solid source molecular beam epitaxy system (MBE) equipped with As/Sb valved cracker cells and Ga/In SUMO[®] cells. On the top of a 253 nm thick GaSb: Be p-type buffer, the device structure consisted of a 675 nm thick p-type InAs/GaSb: Be SLs contact layer, a 2.144 μm InAs/GaSb SLs unintentionally doped active region, a 675 nm thick n-type InAs: Si/GaSb SLs contact layer and capped with a 10 nm thick InAs: Si n-type capping layer. The superlattice design for the absorbing region used 13 monolayers (MLs) of InAs and 7 MLs of GaSb in one period.

The single-pixel photodiodes with diameters ranging from 50-200 μm were fabricated. The samples were processed using standard photolithography and inductively coupled plasma etching techniques with Cl_2 gas [8]. Then, the diodes were dipped in $\text{HCl}:\text{H}_2\text{O}_2:\text{H}_2\text{O}=1:1:10$ solutions for 30 S to remove the native oxide film on the etched mesa sidewalls. Some diodes were passivated with 300 nm thick SiO_2 dielectric layer, using the ICPCVD system at 75 $^\circ\text{C}$, 160 $^\circ\text{C}$ and 350 $^\circ\text{C}$ and the process was carried out under the pressure of 90 mTorr, ICP power of 2400 W and RF power of 150 W. Flow rates were 17 sccm for SiH_4 and 40 sccm for N_2O . Subsequently, an ohmic contact was annealed at 375 $^\circ\text{C}$ for 45 S by depositing Ti (50 nm) /Pt (50 nm) /Au (300 nm) on the bottom and top contact layers of the samples. And then all the unpassivated and passivated samples were wire bonded to a leadless chip carrier for further electrical characterization. The dark current density was measured as a function of applied bias. For the measurement, the diodes were cooled from 300 K to 77 K with a closed cycle cryostat. All results presented in this paper were obtained for devices without antireflective (AR) coating.

Results and discussion

The electrical performance of the unpassivated and SiO_2 -passivation diodes at different deposition temperatures was shown in Figure 1. Comparison with unpassivated samples, the surface leakage current of passivated samples was effectively reduced. And at reverse bias region, it is clearly appeared that the current-density-voltage curve of the SiO_2 dielectric layer performing at low temperature of 75 $^\circ\text{C}$ has the lower dark current and its performance was better than performed in typical temperature 160 $^\circ\text{C}$ and 350 $^\circ\text{C}$. In addition, under forward bias, the diode of the low temperature deposition SiO_2 dielectric layer has a low serial resistance, which is obtained from the current-density-voltage curve and makes this work relevant and useful to the T2SL detector community.

The dark current in a given device is the sum of the diffusion current and the current originated from the GR and from TAT current. While at high bias, the band-to-band tunneling current (BTB) became larger, but photodiodes are normally operated in the low bias regime, and hence, the BTB tunneling current was reasonably neglected.

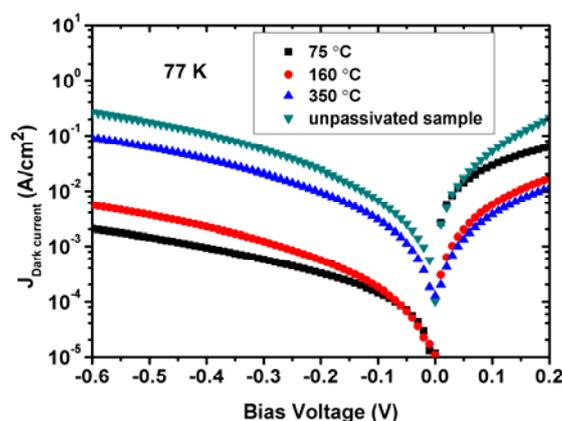


Fig.1 the electrical performance of the SiO_2 -passivation diodes at different deposition temperatures.

The diffusion current [9] 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, V is the applied bias voltage, n_i is the intrinsic carrier concentration in the InAs/GaSb SL structure, N_A and N_D are the p- and n-type doping concentrations, respectively; L_e , L_h and D_e , D_h are the electron and hole diffusion lengths and diffusion coefficients. The fitting parameters whose values that are taken from being temperature dependent, were extracted from Hall measurements [10].

The GR current is due to various GR processes taking place inside the diode, such as Shockley-Read-Hall (SRH). While the photodiode operates at small reverse bias, carriers in the depletion region are swept out of the electrodes. As a result, the carrier concentrations become too small for a three-particle process to significantly contribute to the GR current. So the dominant process is the SRH and the general expression for SRH GR current [11] at reverse bias is given by

$$J_{GR} = \frac{qn_i W}{\sqrt{\tau_n \tau_p}} \frac{\sinh(-qV/2kT)}{q(V_B - V)/2kT} f(V) \quad (2)$$

Where W is the depletion width which is dependent on the applied bias V and the built-in potential V_B , and k is the Boltzmann constant.

The contribution of the TAT current [12] can be expressed as follows:

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

Where m_e is the tunneling effective mass, E_g is the effective bandgap of SLs material, h is Planck's

constant, M^2 is the matrix element associated with the trap potential assumed to be $10^{-23} \text{ eV}^2 \text{ cm}^3$, $F(V)$

is the electric field strength across the depletion region, E_t is the location of the trap level below the

effective conduction band edge, and N_T is the trap density that participates in the tunneling process.

According to the equations above, the dominant mechanism of dark current in photodiodes varies with temperature. All mechanisms become stronger at higher temperature. However, their temperature dependence are not the same. It results in different dominating mechanisms at different temperature regimes. At high temperature, diffusion is the strongest mechanism since it has the greatest dependence on temperature, and the diffusion is affected by temperature 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 diffusion current decreases faster, and will get smaller, where the GR current becomes dominant. It exhibits linearity with a slope of $\frac{1}{2} qE_g/k$ as depicted in Eq. (2).

Shown in Figure. 2 is the temperature dependence of experimental and theoretical dark current under 100 mV reverse bias. For the unpassivated diode (black square dots), it shows a higher dark current-limited at temperatures ranging from 77 to 300 K, which couldn't identify the detail of each dark current contribution to the total dark current. While for SiO_2 passivated diodes, In Figure 2, two regimes can be easily observed above and below $T=150$ K. For temperature higher than 150 K, the diode exhibits Arrhenius-type behavior and fits well to the diffusion-limited behavior $\exp(-qE_g/kT)$ as depicted in Eq. (1). The energy of the diffusion current extracted from the Arrhenius plot was determined to be 140 meV. Since the temperature was lowered down from 150 K to 77 K, the GR-limited mechanism can fit it well. But when the temperatures were even further decreased, the GR current became smaller, it was necessary to know that the importance of taking the other mechanisms into account to understand the performance of the photodiodes. The dark current mechanism was discussed at selected temperatures in detail later.

In order to identify bias dependent dominant current components, analysis of the dark current contributions was made on current density-voltage (J-V) curves recorded at 77 K. The dark current is fitted using formula (1), (2) and (3). We decompose the dark current into its diffusion component

and the GR and TAT. According to the fitting curves, In Figure. 3(a), at 77 K, the GR current becomes the most part contributing to the total dark current and presents the diffusion current was not the dominant mechanism. We also plot the simulation of the pure TAT component of the dark current if the GR current is not taken into account. The model with GR mechanism describes accurately the dark current at low applied bias, but cannot explain the value of the dark current at high bias, and the TAT cannot be neglected at low temperatures. Fourier transform infrared spectroscopy and a liquid nitrogen cooled cold finger system was used to measure the spectral response of the photodiodes.

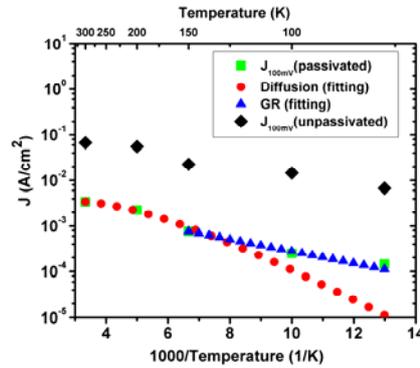


Fig.2 Temperature dependent dark current density (-100 mV) for unpassivated and SiO₂-passivated photodiodes.

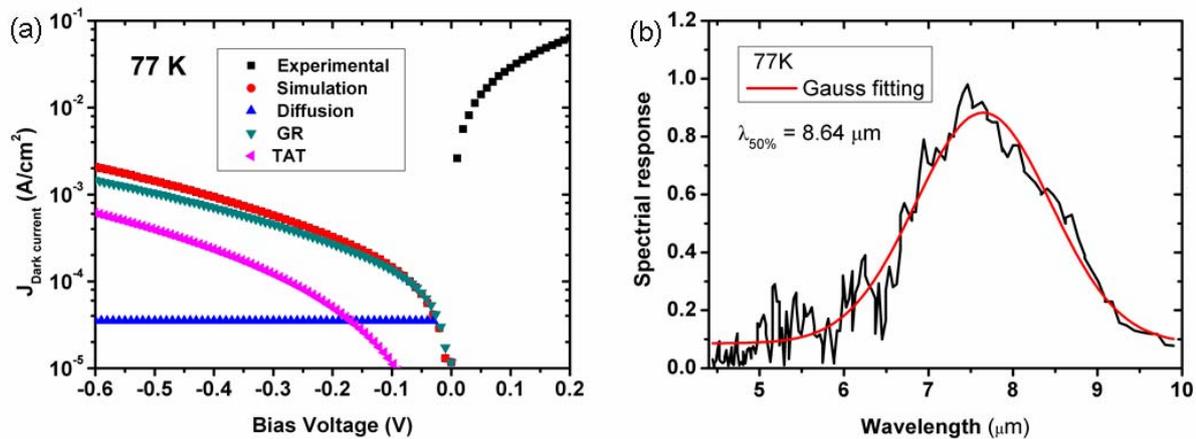


Fig. 3(a) Modeled dark current density vs voltage of SiO₂-passivated photodiodes at 77 K and the corresponding spectral response(b).

Figure. 3(b) shows the spectral response vs wavelength graph of the SiO₂ passivated sample, which is performed at lower temperature deposition of 75 °C, and the corresponding 50% cut-off wavelength is ~8.64 μm. This is consistent with direct measurement of the spectral response.

Conclusions

We have presented a type II superlattice photodiode, which is normally designed as a p-i-n junction with i-region unintentionally doped. The SiO₂ dielectric layer deposition carried out in the ICPCVD system at 75 °C. Comparison of the passivated and unpassivated photodiodes, the surface leakage current is significantly reduced. The total dark current of the photodiodes is expressed as the sum of diffusion and GR and TAT. The fitting with experimental results shows good agreement between theory and experiment in the range of reverse biases (0-0.6 V) considered.

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