6th International Conference on Electrical and Computer Engineering
ICECE 2010, 18-20 December 2010, Dhaka, Bangladesh

Analysis of Zero-Bias Resistance Area Product for InGaSb PIN Photodiodes

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Abstract— **This paper represents a model of zero-bias resistance area product of InGaSb PIN photodiodes grown on InGaSb metamorphic layer through the analysis of surface leakage and bulk current components of these photodiodes. The model is further developed by considering effects of dislocation density in the diodes. Different optoelectronic properties of the material are extracted by fitting the obtained models with experimental data, such as the values of electron and hole diffusion lengths (L_n and L_p), surface recombination velocity inside the material and at the exposed mesa edges (S_n and s) are found to be 70.34 μm, 6.44 μm, 2.2584×10^2 cm/s and 4.1195×10^5 cm/s, respectively. The extracted dislocation density is 6.67×10^8 cm^{-2} which is nearly close to the measured value of ~$2\text{-}5\times10^8$ cm^{-2} for this type of photodiodes.**

Keywords— **R_0A product, InGaSb, PIN photodiode, Dislocation, Surface leakage.**

I. Introduction

In recent times, there has been a growing interest in GaSb and related materials for potential new device applications originating from their excellent optical and electronic properties. Optoelectronic devices incorporating GaSb-based materials are suitable for mid-infrared (2-5μm) applications and electronic devices with antimony-containing materials are known for their use in low-power, high-speed electronics. One particular antimony-containing easy-to-grow ternary is InGaSb which is finding ever increasing applications as photodetectors and lasers operating adequately well in the 1.7-6.9μm wavelength range, and which has interesting biomedical and security applications. One specific example is the use of InGaSb-based photodetectors in toxic gas sensing systems. [1]

Metamorphic buffers allow for the growth of layers of materials with a desired lattice constant on a substrate of a different lattice constant. Metamorphic growth is initiated on a standard substrate and by varying the composition of the subsequent layers, either gradually or in steps, it is ultimately possible to provide a new surface layer with a different lattice constant. The lattice mismatch is accommodated through the formation of dislocations mostly confined to the buffer layers, thus allowing the topmost metamorphic layer to be used as a pseudosubstrate for subsequent device structure growth. Hence, the use of metamorphic layers provides the device designer with increased flexibility to "band gap engineer" device structures with properties not accessible using available binary substrates. In the present work, we have grown step-graded metamorphic layers of $In_xGa_{1-x}Sb$ on GaSb with terminating composition x=0.15. After characterizing the quality of the metamorphic layers, we have successfully regrown *p-i-n* diodes of various sizes on one of those samples having low dislocations with satisfactory dark current characteristics.

In this paper, at first the bulk diffusion, generation-recombination (g-r), and surface-related leakage current components in InGaSb based photodiodes are evaluated using an earlier developed model for mercury cadmium telluride (MCT) based photodetectors [2]. Subsequently the effect of dislocation density on surface leakage current component [3] is included with this model. Both the models are fitted to the experimental data [4], [5] obtained for the fabricated devices to extract material parameters, for instance minority carrier diffusion lengths (L_p, L_n) and surface recombination velocity (S_n and s) afterwards. Also the value of dislocation density existing in the diode is extracted through this modelling.

II. Experimental Details

All the layers of the metamorphic samples were grown in a Gas Source Molecular Beam Epitaxy (GSMBE) system manufactured by SVT Associates (SVTA). A complete experimental detail is depicted in ref [4].

The epitaxial layer structure for the metamorphic sample starts with a GaSb buffer (0.1 to 0.25 μm) on the GaSb substrate, followed by a sequence of four buffer layers of $In_xGa_{1-x}Sb$ grown at various temperatures (450°C to 540°C), where x was varied in equal increments of x = 0.03. Each buffer layer had a thickness of 250 nm. The step-graded buffer layers were terminated by the final metamorphic layer with composition x = 0.15. The thickness of the top metamorphic layer was between 1.1 and 1.5 μm. Finally, a fully strained 40 nm GaSb cap-layer was grown on top of the metamorphic layer to simplify x-ray characterization. The samples were nominally 2×10^{18} cm^{-3} p-doped by a beryllium solid-source cell operating at 785°C and 1.5×10^{18} cm^{-3} n-doped by a titanium source. The undoped InGaSb is unintentionally p-type and has a doping concentration of 2.4×10^{16} cm^{-3}. All samples had 250 nm thick buffer layers. InGaSb PIN homojunction diodes, lattice-matched to the underlying top metamorphic layer, were then epitaxially re-grown with the same desorption procedure as discussed above to remove surface contaminants. Standard photolithography was followed to fabricate diodes of various sizes and dark current measurements were performed.

III. Model

The device schematic used for the calculation is shown in Fig. 1. We have considered an n-i-p diode. Figure 2 depicts absolute value of total leakage current density as a function of applied reverse bias voltage for 40 and 100 μm square diodes having the largest and the smallest perimeter-to-area ratio (p/A), respectively, among all the diodes that had been fabricated [5]. If the total leakage current is consisted of diffusion, generation-recombination and surface leakage current, it can expressed as,

$$J_T = J_D + J_{g-r} + \left(\frac{p}{A}\right) J_S \tag{1}$$

where J_T is total leakage current density, J_D is diffusion current density of minority carrier, J_{g-r} is carrier generation current at bulk depletion region, J_S is surface leakage current at exposed mesa edge and p/A is perimeter-to-area ratio of the diode.

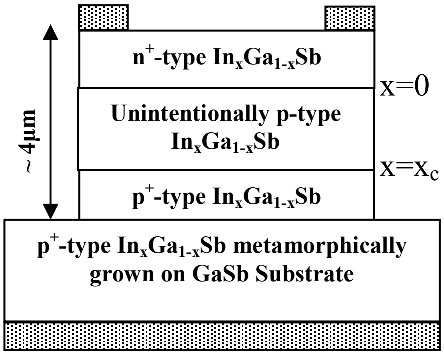

Fig. 1 Device schematic structure

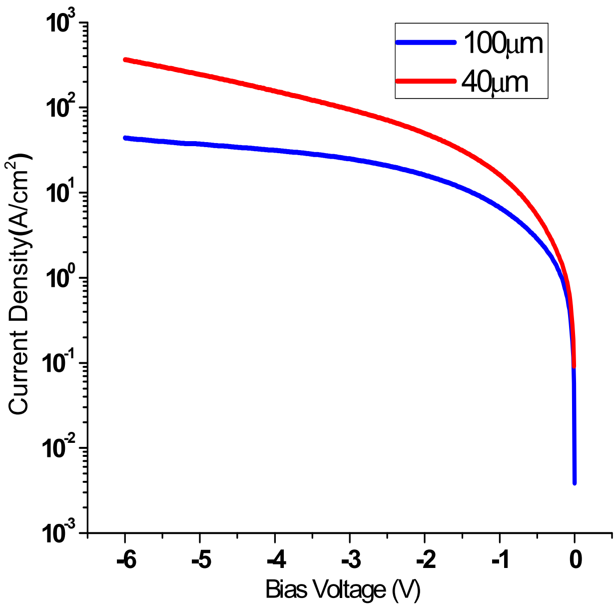

Fig. 2 Total leakage current-voltage curves for 40 μm and 100 μm square $In_xGa_{1-x}Sb$ (x = 0.107) PIN-diode at room temperature and under dark condition.

Figure 3 depicts the reverse bias leakage current density as a function of perimeter-to-area ratio of 40 and 100 μm square photodiodes at -0.5 Volt. From this it is clear that the negative reverse leakage current density increases with the increase in perimeter-to-area ratio.

From equation (1) it can be seen that if surface leakage is a dominant factor, then as the perimeter-to-area ratio increases that is device dimension is reduced, total leakage current (J_T) increases. Thus, it can be concluded from Fig. 3 that the leakage current in InGaSb PIN photodiodes is dominated by the surface leakage currents as is expected from other photodiode materials also [6].

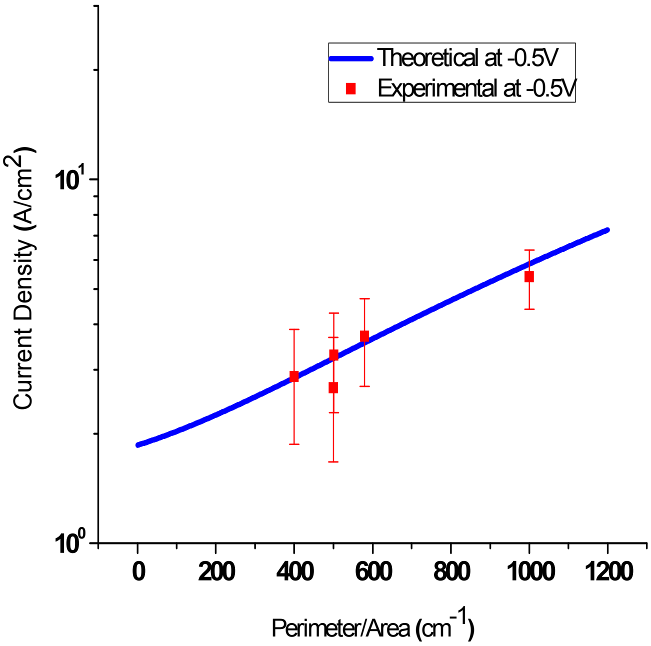

Fig. 3 Total leakage current at -0.5V for $In_xGa_{1-x}Sb$ (x = 0.107) PIN-diode at room temperature and under dark condition.

The model for zero-bias resistance area product of InGaSb photodiodes grown on InGaSb metamorphic layer is firstly developed by considering different surface leakage and bulk current components of the diode. Dislocations are considered to play a dominant role in shaping the variation of zero-bias resistance-area product in the low temperature range [7]. Dislocations physically act as a shunt resistance and side by side influence the diode impedance through their effect on minority carrier lifetime. The shunt resistance contribution due to a dislocation has been found to be a very sensitive function of the charge around its core. So in the present model, the effect of dislocation density (N) on the surface leakage current component is added. As a result by considering the dislocation effect, the obtained parameters value of different material is changed which differs our model from the one developed by V. Bhagwat et al [6] for GaInAsSb photodiodes.

A. Model by Considering Leakage Current Components

The model for MCT considered semi-infinite base by assuming much smaller minority carrier diffusion length. In the current part for InGaSb photodiode without considering dislocation effect explicitly, we have adapted the model of ref [6]. By assuming that the thickness of n and p regions of the diode is much smaller than the minority carrier diffusion length, the zero-bias resistance area product model for the current mesa diode is given by,

$$\frac{1}{R_0 A} = \frac{(L_n - x_p)^2}{4}\left(\frac{1}{(R_0 A_S)_S}\right)\left(\frac{p}{A}\right)^2 + L_n\left(\frac{1}{(R_0 A_S)_S}\right)\left(\frac{p}{A}\right) + \left(\frac{1}{R_D A_j} + \frac{1}{(R_0 A)_{g-r}}\right) \tag{2}$$

where $(R_0A_S)_S$ is the surface leakage component, R_DA_j is the bulk diffusion and $(R_0A)_{g\text{-}r}$ is the component from recombination at the bulk space charge region of the diode. L_n is the minority carrier diffusion length for the p-side of the diode, x_p is the thickness of mesa exposed p region of the diode, p is perimeter and A is area of the diode.

The diffusion component is affected by the recombination of minority carriers at the undoped InGaSb and p^+-InGaSb interface where there is a concentration gradient of holes giving rise to a surface recombination velocity. The expression is given by ref [7],

$$\frac{1}{R_DA_j}=\frac{q^2n_i^2}{kT}\left\{\frac{L_p}{\tau_pN_D}+\frac{L_n}{\tau_nN_I}\left[\frac{\left(\frac{S_n}{D_n}-\frac{1}{L_n}\right)e^{\frac{x_c}{L_n}}-\left(\frac{S_n}{D_n}+\frac{1}{L_n}\right)e^{-\frac{x_c}{L_n}}}{\left(\frac{S_n}{D_n}-\frac{1}{L_n}\right)e^{\frac{x_c}{L_n}}+\left(\frac{S_n}{D_n}+\frac{1}{L_n}\right)e^{-\frac{x_c}{L_n}}}\right]\right\}$$

(3)

where q is the electronic charge, k is Boltzmann's constant, T is the junction temperature, n_i (=6.29×10^{12}cm^{-3} for energy bandgap E_g=0.62eV at 300K) is the intrinsic carrier concentration, S_n is the surface recombination velocity at the i-InGaSb/p-InGaSb interface, x_c is the position of i-InGaSb/p-InGaSb interface, τ_n and τ_p are the minority carrier diffusion lifetimes, N_A and N_D are the doping densities, and D_p and D_n are the minority carrier diffusion constants in the p and n material, respectively. The diffusion constants are obtained from the appropriate carrier mobilities, μ_p and μ_n, using the Einstein relation, $D/\mu= kT/q$.

The zero-bias resistance area product from generation-recombination at the bulk region of the diode is given by,

$$(R_0A)_{g-r}=\frac{\tau_pV_{bi}}{qn_iW} \tag{4}$$

where V_{bi} is the built-in potential and W is the depletion layer width.

The surface leakage component for zero-bias resistance is given as [7],

$$(R_0A_S)_S=\frac{V_{bi}D}{4qn_iWs} \tag{5}$$

where D is the width of the diode and s is the surface recombination velocity at the exposed mesa edge. The area A_S can be written as irrespective of square or circular mesa sample [2],

$$A_S=\frac{L_n^2}{4}\frac{p^2}{A}+pL_n \tag{6}$$

The actual zero bias resistance is a parallel combination of the resistances arising from the contribution from diffusion, g-r, and surface leakage and other non-ideal effects.

B. Model by Considering Dislocation

The model of zero-bias resistance must take into account the effect of dislocation in the diode material. The effect of dislocations on minority carrier lifetime is depicted by V. Gopal et al [3] for MCT. Approaching in similar fashion the actual minority carrier diffusion length is expressed as

$$\frac{1}{L_n^2}=\frac{1}{L_{n0}^2}+\frac{2\pi masN}{D_n} \tag{7}$$

where L_{n0} is the minority carrier diffusion length in the absence of dislocation in the material, m is an integer with minimum value of unity, a (=6.14Å) is lattice constant of the material. The expression for minority carrier lifetime is given as,

$$\frac{1}{\tau_n}=\frac{1}{\tau_{n0}}+2\pi masN \tag{8}$$

where τ_{n0} is the minority carrier lifetime in the diffusion free material.

The contribution from surface leakage to the zero-bias resistance can be expressed as [3],

$$R_S=\frac{kT}{2\pi q^2n_ismat} \tag{9}$$

$$(R_0A_S)_S=\frac{R_s\times A_S}{N} \tag{10}$$

Here R_s is the contribution from each individual dislocation, N is the dislocation density within the thickness t of the diode and A_s comes from equation (6). The expression for zero-bias resistance then remains the same as in equation (2).

IV. Results & Discussion

There are three distinct cases to consider for the diodes depending on which component of the leakage current dominates. These are the following:

Case 1: It represents a situation in which diffusion current density dominates and the surface and interface leakage current densities are relatively small. Here $(R_0A_S)_S$ is assumed to be orders of magnitude greater than R_DA_j and $(R_0A)_{g\text{-}r}$.

Case 2: It corresponds to a situation in which surface leakage current density plays a dominant role in comparison with the diffusion and g-r current density, i.e. $(R_0A_S)_S$ is assumed to be orders of magnitude smaller than R_DA_j and $(R_0A)_{g\text{-}r}$.

Case 3: It represents a situation in which diffusion current density is comparable with the surface and interface leakage current densities. It is assumed that $1/(R_0A_S)_S=(1/R_DA_j+1/(R_0A)_{g-r})$.

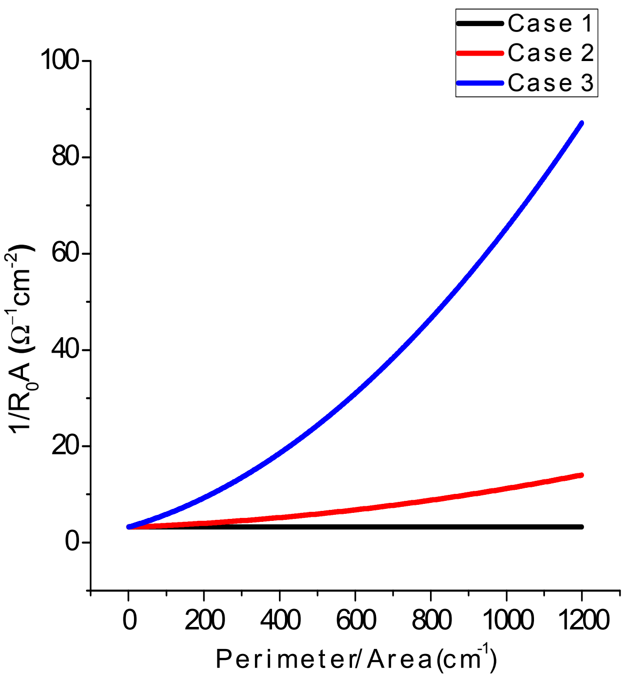

Fig. 4 Effects of surface and bulk leakage currents on the variation of $1/R_0A$ as a function of perimeter-to-area ratio (p/A) of the diode.

For the calculation 100 μm square mesa $In_xGa_{1-x}Sb$ (x = 0.107) PIN-diode is used. Carrier mobilities μ_p and μ_n are equal to 468 and 2164 cm^2/V-s respectively. Figure 5 shows the theoretical plot fitted with the experimentally achieved data for the model described in Section III. From this figure we see that the experimental data [4], [5] fits well with Case-2 described above that the diode is surface leakage current dominant.

From the fitting we find the values of L_n, L_p, S_n and s as 70.34 μm, 6.44 μm, 2.2584×10^2 cm/s and 2.7464×10^7 cm/s, respectively. After including dislocation effect into the model we get L_{n0} to be 73.73 μm and s to be 4.1195×10^5 cm/s. Dislocation density in the present sample is extracted as 6.67×10^8 cm^{-2} which is almost equal to the measured value of ~2-5×10^8 cm^{-2} [4], [5] for this type of photodiodes.

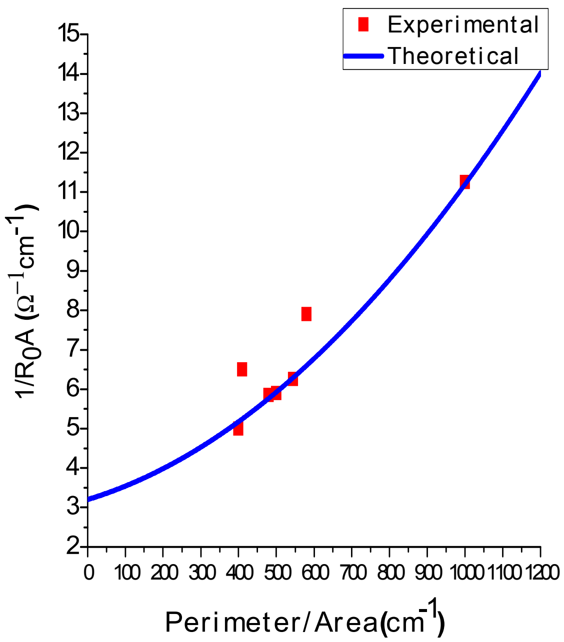

Fig. 5 Experimental data and calculated value from equation (1-5)

The value of L_p that is diffusion length of minority carrier holes is considerably less than that for electrons. The reason behind this is that μ_p is significantly less than μ_n in the present diode. So overall a shorter minority carrier lifetime for holes (τ_p=3.43×10^{-8} s) is observed as compared to the lifetime for electrons (τ_n=8.85×10^{-7} s).

From the model we find the value of surface recombination velocity at the exposed mesa edge s to be orders of magnitude greater than the surface recombination velocity at the bulk material S_n. This indicates the necessity of passivation of the diode to reduce surface leakage current. These values of the surface recombination velocities are close to the values obtained for GaInAsSb photodiodes [6] as 2250 cm/s and 10^6 cm/s, respectively. Therefore these are the expected values from those diodes where Sb is the dominant material ($In_{0.13}Ga_{0.87}As_{0.11}Sb_{0.89}$) [6]. Also we can see dislocation tends to increase the surface leakage current. A detail analysis of this effect can be made as is done for MCT photodiodes [7].

V. Conclusions

In this paper, we have studied the contributions of various leakage mechanisms to the zero-bias resistance area product of InGaSb PIN photodiodes by analytical techniques. An increase in total leakage current in InGaSb PIN photodiode is observed with the reduction of device dimension. A surface leakage current dominated mechanism is noticed through the nonlinear dependence of the inverse of the zero-bias resistance-area product ($1/R_0A$) on the perimeter to area ratio (p/A). Effect of dislocation is also considered later in the model. By fitting the model to the experimental data [4], [5], we obtain the diffusion lengths of electrons and holes to be 70.34 μm and 6.44 μm, respectively. The surface recombination velocities at the interface and at the exposed mesa edges are observed to be 2.2584×10^2 cm/s and 4.1195×10^5 cm/s, respectively. The parameter values obtained through this model can be further scrutinized taking into account additional effects like Zener tunnelling [8] or more probably trap assisted tunnelling [9] and others as mentioned in ref [2]. Detail analysis of other effects such as temperature effect on zero-bias resistance-area product of InGaSb PIN photodiodes, surface recombination velocity, the effect of dislocation density and temperature dependence of dislocation shunt resistance considering space charge density around the core of dislocation etc. are ongoing which is subjected to another publication.

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