Modeling of electrical characteristics of midwave type II InAs/GaSb strain layer superlattice diodes

V. Gopal,1 E. Plis,2 J.-B. Rodriguez,2 C. E. Jones,3 L. Faraone,1 and S. Krishna1,2,a

1School of Electrical, Electronic and Computer Engineering, The University of Western Australia, Crawley, Western Australia 6009, Australia
2Center for High Technology Materials, Department of Electrical and Computer Engineering, University of New Mexico, Albuquerque, New Mexico 87106, USA
3Lockheed Martin-Santa Barbara Focal Plane, 346 Bollay Drive, Goleta, California 93117, USA

(Received 4 April 2008; accepted 1 November 2008; published online 18 December 2008)

This paper reports the results of modeling of electrical characteristics of midinfrared type II InAs/GaSb strain layer superlattice (SLS) diode with p-on-n polarity. Bulk based model with the effective band gap of SLS material has been used in modeling of the experimental data. Temperature dependence of zero-bias resistance area product ($R_dA$) and bias dependent dynamic resistance of the diode have been analyzed in detail to investigate dark current contributing mechanisms that are limiting the electrical performance of the diode. $R_dA$ of the diode is found to be limited by thermal diffusion currents at higher temperatures and Ohmic shunt resistance contribution limits it at low temperatures $\sim 82$ K.


I. INTRODUCTION

In recent years InAs/GaSb type II strained layer superlattices (SLSs) have emerged as a promising infrared detector material for thermal imaging systems.1,2 In addition to the similarities of band gap engineering and high optical absorption coefficient3 with the popularly used mercury cadmium telluride material, SLS provides a high degree of material uniformity over large areas and the possibility of reducing dark currents due to predicted longer Auger recombination rates.4 In addition, the band structure of the SLS can be engineered for reduced noise at higher temperatures.5 Thus SLS offers a number of advantages that make it an attractive infrared detector material for developing infrared imaging arrays operating at higher temperatures. Presently, all investigations on SLS based detectors are limited to n-on-p configuration of the diode. Keeping in mind the easy availability of readout integrated circuits, such as Indigo 9705 or SBF 130, that work6 with the p-on-n configuration of the diodes, we have recently reported7 p-on-n configuration of the diode with the aim of developing high operating temperature imaging arrays. This paper reports the results of modeling of electrical characteristics of type II InAs/GaSb SLS diode with p-on-n polarity. Bulk based model with the effective band gap of SLS material has been used in modeling of the experimental data. Temperature dependence of zero-bias resistance area product ($R_dA$) and bias dependent dynamic resistance of the diode have been analyzed in detail to investigate dark current contributing mechanisms that are limiting the electrical performance of the diode. $R_dA$ of the diode is found to be limited by thermal diffusion currents at higher temperatures and Ohmic shunt resistance contribution limits it at low temperatures $\sim 82$ K. The choice for modeling the dynamic resistance characteristics of the diodes is guided by the fact that the variations in the dynamic resistance of a given diode are much more sensitive to the dark current contributing mechanisms than the variations in the current by itself. In addition zero-bias dynamic impedance of the diode is most often used as a figure of merit for IR detectors.

II. EXPERIMENTAL METHODS

Samples presented in this paper have been grown by molecular beam epitaxy in a VG-80 system. The detailed growth procedure has been reported elsewhere.9 The device structure consists of $\sim 1.5$ $\mu$m 8 ML (monolayer) InAs/8 ML GaSb SL (300 periods) unintentionally doped absorber ($n \sim 4.7 \times 10^{16}$ cm$^{-3}$) grown on top of 400 nm thick n-type contact layer (consisting of 8 ML InAs/8 ML GaSb SL with Si-doped InAs layers, $n \sim 1 \times 10^{18}$ cm$^{-3}$). This was followed by a 50 nm GaSb layer doped p-type ($p \sim 2 \times 10^{18}$ cm$^{-3}$) with beryllium which served as the top contact (Fig. 1). Processing details have been reported earlier.8 All devices, regardless of size, showed a similar spectrum with $\lambda_{\text{cutoff}} \sim 4.2$ $\mu$m at 77 K and $\sim 5$ $\mu$m at 300 K. External QE was measured to be equal to $\sim 18\%$ at $-0.5$ V and $\sim 8\%$ at zero bias.

---

*aElectronic mail: s.krishna@chtm.unm.edu.

FIG. 1. Schematic of heterojunction p-on-n superlattice mesadiode.
derivatives are given by

given below.

count while modeling the narrow band gap material diodes is
purpose of modeling. A brief summary of the known contrib-
discussion can be thus treated as one-sided junction for the
thermal diffusion current of the diode. The diode under
contact material with its high doping contributes negligibly to
omitted because of its higher band gap compared to the ef-
mal contribution from GaSb to the diode current may be

III. THEORETICAL MODEL

Bulk based model\textsuperscript{10–13} with effective band gap of SLS
material will be used to model the experimental data. A sche-
matic of the heterojunction \textit{p}-on-\textit{n} SLS diodes used in the
present study is shown in Fig. 1. Note that the junction is
located at the \textit{p}-GaSb/\textit{n}-SLS material interface. The flat
band diagram at this interface\textsuperscript{14} is shown in Fig. 2. The
thermal contribution from GaSb to the diode current may be
omitted because of its higher band gap compared to the ef-
effective band gap of SLS material. Similarly a thinner (100
periods compared to 300 periods of absorber layer) SLS con-
tact material with its high doping contributes negligibly to
the thermal diffusion current of the diode. The diode under
discussion can be thus treated as one-sided junction for the
purpose of modeling. A brief summary of the known contrib-
uting dark current components that have been taken into ac-
count while modeling the narrow band gap material diodes is
given below.

A. DIFFUSION CURRENT \((I_{\text{dif}})\)

In the one-sided junction, the thermal diffusion of the
minority carriers from the \textit{n}-type SLS material is one of the
components of the dark current that may be calculated by
using the following expression:\textsuperscript{15}

\[
I_{\text{dif}} = \frac{q A n_i^2}{N_d} \left( \frac{kT \mu_h}{\sqrt{2 \pi q \tau_n}} \right)^{1/2} \frac{d}{L_h} \exp \left( \frac{qV}{kT} - 1 \right). \tag{1}
\]

\(N_d\) is the donor concentration on the \textit{n} side of the junction, \(n_i\)
is the intrinsic carrier concentration, \(A\) is the junction area, \(V\)
is the diode bias voltage, \(d\) is the thickness of the \textit{n} region, \(\tau_n\)
is the hole lifetime, \(\mu_h\) is the hole mobility, and \(L_h\) is the hole
diffusion length. The associated dynamic resistance and its
derivatives are given by

\[
R_{\text{dif}}^{-1} = \left( \frac{q}{kT} \right) \frac{q A n_i^2}{N_d} \left( \frac{kT \mu_h}{\sqrt{2 \pi q \tau_n}} \right)^{1/2} \frac{d}{L_h} \exp \left( \frac{qV}{kT} \right), \tag{2}
\]

\[
\frac{d^2 I_{\text{dif}}}{dV^2} = \left( \frac{q}{kT} \right)^2 \frac{q A n_i^2}{N_d} \left( \frac{kT \mu_h}{\sqrt{2 \pi q \tau_n}} \right)^{1/2} \frac{d}{L_h} \exp \left( \frac{qV}{kT} \right). \tag{3}
\]

Equation (3) and similar expressions for other dark current
contributing mechanisms will be required later to determine
the trap density \(N_T\) from the experimental data.

B. GENERATION-RECOMBINATION CURRENT \((I_{\text{gr}})\)

In this type of current mechanism, defects within the
depletion region act as intermediate states (usually referred
to as Shockley–Read or simply SR centers) for the thermal
generation and recombination of carriers. Sah \textit{et al.} analyzed
these currents and developed equations for the idealized
case.\textsuperscript{16} Unfortunately these do not yield a closed form
solution for describing the complete \(I-V\) characteristics. Alter-
avatively we use the simplification Schololar \textit{et al.}\textsuperscript{17} of the origi-

The voltage dependent depletion region
width \(W_{\text{dep}}\) will be obtained in the homojunction approxima-
tion by the following expression:\textsuperscript{10,12}

\[
W_{\text{dep}} = \left[ \frac{2 \epsilon_\infty \epsilon_r (N_d + N_a) V_t}{q N_d N_a} \right]^{1/2},
\]

\(V_t = V_{bi} - V\).

Here \(V\) is the external bias applied to the junction, \(V_{bi}\) is the
built-in potential, \(\epsilon_r\) is the permittivity of free space, and \(\epsilon_\infty\)
is the static dielectric constant of SLS material.

It may be emphasized here that a rigorous heterojunction
treatment\textsuperscript{18} leads to Eq. (6) if the static dielectric constants of
the materials on the two sides of the junction are approxi-
mately equal. With GaSb as one of the constituents of SLS
material, use of Eq. (6) in modeling the diode depicted in
Fig. 1 may be justified. Similarly the built-in potential \(V_{bi}=(kT/q \ln[N_a N_d/n_i^2])\) may also be approximated to a ho-
mojunction case. Note that most of the depletion width will
be in the SLS material on account of higher carrier concentra-
tion on the \textit{p} side.

For the ease of application, the \(I_{\text{gr}}\) current can be rewritten as

\[
I_{gr}\mid_{V<0} = 2A_{gr} \frac{V}{\sqrt{V_t}}; \tag{7}
\]

\[
I_{gr}\mid_{V>0} = 4A_{gr} \frac{kT}{qV_t^{1/2}} \sinh \left( \frac{qV}{2kT} \right), \tag{8}
\]

\(A_{gr}\) is the voltage independent term in Eqs. (7) and (8). The
associated dynamic resistance and its derivatives are given by
\[
[R_{gr}^{-1}]_{V<0} = 2A_g \left[ \frac{1}{V_t^{1/2}} + \frac{V}{2V_t^{3/2}} \right],
\]
\[
[R_{gr}^{-1}]_{V>0} = 2A_g \left[ \frac{KT}{qV_t^{3/2}} \sinh \left( \frac{qV}{2kT} \right) + \frac{1}{V_t^{1/2}} \cosh \left( \frac{qV}{2kT} \right) \right].
\]
\[
\frac{\partial^2 I}{\partial V^2} = 2A_g \left[ \frac{1}{V_t^{1/2}} + \frac{3V}{4V_t^{3/2}} \right],
\]
\[
\frac{\partial^2 I}{\partial V^2} = 2A_g \left[ \frac{3KT}{2qV_t^{5/2} + qV_t^{3/2}} \sinh \left( \frac{qV}{2kT} \right) + \left( \frac{1}{V_t^{1/2}} \right) \cosh \left( \frac{qV}{2kT} \right) \right].
\]

C. Trap-assisted-tunneling current \( I_{\text{TAT}} \)

Following the previously published work, the contribution of trap-assisted-tunneling (TAT) current can be expressed as follows:

\[
I_{\text{TAT}} = \frac{\pi^2 q^2 Am_v M^2 N_T}{h^3(E_g - E_i)} \times \exp \left\{ - \frac{8\pi(2m_e)^{1/2}(E_g - E_i)^{3/2}}{[3qhF(V)]} \right\},
\]

where \( m_e \) is the tunneling effective mass, \( E_g \) is the effective band gap of SLS material, \( h \) is Planck’s constant, \( M \) 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, \( E_i \) is the location of the trap levels below the effective conduction band edge, and \( N_T \) is the trap density that participates in the tunneling process.

The associated dynamic resistance and its derivatives are given by

\[
(R_{\text{TAT}})^{-1} = \frac{2q^3 A \pi^2 m_v M^2}{h^3(E_g - E_i)} N_T \exp \left( - \frac{B}{V_t^{1/2}} \right) \left( 1 + \frac{B}{2V_t^{3/2}} \right),
\]

\[
\frac{\partial^2 I_{\text{TAT}}}{\partial V^2} = \frac{2q^3 A \pi^2 m_v M^2}{h^3(E_g - E_i)} N_T \exp \left( - \frac{B}{V_t^{1/2}} \right) \left( \frac{B}{4V_t^{3/2}} + \frac{B^2}{4V_t^2} \right),
\]

\[
B = \frac{8\pi(2m_e)^{1/2}(E_g - E_i)^{3/2}}{3qh \left( \frac{2qN_T}{\epsilon_0 \epsilon_r} \right)^{1/2}}.
\]

The above value of \( B \) corresponds to a triangular shape barrier.

D. Ohmic component of current \( I_{\text{sh}} \)

Most often a practical diode exhibits an excess current component that obeys Ohm’s law, i.e.,

\[
I_{\text{sh}} = \frac{V}{R_{\text{sh}}}. \tag{17}
\]

\( V \) is the applied voltage across the junction and \( R_{\text{sh}} \) is the diode shunt resistance. The surface leakage currents and the dislocations in the material that intersect the junction are generally held responsible as a possible source for this part of excess current.

E. Determination of Ohmic shunt resistance and trap density from differential diode resistance versus voltage \( R_d - V \) characteristics

It is known that \( R_d - V \) characteristics of the diode exhibit a peak in the low or medium reverse bias region if TAT was a contributing mechanism to the dark current. It has been already shown that the position of this peak can be exploited to estimate the trap density \( N_T \) that contributes to TAT and component of Ohmic shunt resistance \( R_{\text{sh}} \) as explained below.

The peak position in \( R_d - V \) characteristics corresponds to the condition

\[
\frac{\partial R_d}{\partial V} = 0. \tag{18}
\]

\( R_d \), the resultant dynamic resistance, is the sum of all the contributing impedances:

\[
\frac{1}{R_d} = \frac{1}{R_{\text{dif}}} + \frac{1}{R_{\text{gr}}} + \frac{1}{R_{\text{TAT}}} + \frac{1}{R_{\text{sh}}}. \tag{19}
\]

An expression for the trap density \( N_T \), obtained from mathematical manipulation of Eqs. (3), (11), (12), (15), (18), and (19) is given below,

\[
N_T = \frac{2q^3 A \pi^2 m_v M^2}{h^3(E_g - E_i)} \exp \left( - \frac{B}{V_t^{1/2}} \right) \left( \frac{B}{4V_t^{3/2}} + \frac{B^2}{4V_t^2} \right), \quad \text{at} \quad V = V_m.
\]

(20)

\( V_m \) corresponds to the value of applied voltage \( V \) at the peak position. Since all the parameters on the right hand side of the above equation are generally known for the given diode, the density of traps responsible for TAT can be estimated in a straightforward manner from the observed position of the maximum. It may be noted here that the above estimate of \( N_T \) is practically independent of Ohmic current contribution since \( \partial R_{\text{sh}}/\partial V \approx 0 \) (shunt resistance \( R_{\text{sh}} \) is independent of applied voltage \( V \)). This situation allows us to further obtain an estimate of shunt resistance \( R_{\text{sh}} \) from a comparison of experimental measured peak dynamic resistance and theoretically calculated resultant dynamic resistance due to TAT (making use of estimated \( N_T \), \( gr \), and thermal diffusion current contributions).

Contribution of direct band-to-band (BTB) tunneling has been ignored above, as the case under discussion correspond to a midwave infrared diode. BTB is found to be effective at relatively higher reverse bias voltages even in long-wavelength diodes.
All the transport parameters used in modeling of the experimental results refer to the conduction of the carriers perpendicular to the layered structure. The parameters whose values are taken from the published \(^{10-14}\) literature are \(\mu_c = 1100 \text{ cm}^2/\text{V s}\) and \(\mu_h = 100 \text{ cm}^2/\text{V s}\). The temperature dependence of the band gap of SL material was included in modeling by the following expression:

\[
E_g(T) = 0.310 + 2.610 \times 10^{-7} T(1 - 1.847 T)
\]

The above expression was obtained by fitting the temperature dependence of the band gap estimated from the measured spectral response of the SL detectors.\(^3\)

The intrinsic carrier concentration was calculated in the parabolic energy band approximation from the following relation:

\[
n_i = 2\left[2\pi k T/\hbar^2\right]^{3/2}(m_c m_h)^{1/2} \exp(-E_g/2kT).
\]

\(m_0\) is the free electron mass. We used \(m_c = 0.03m_0\) and \(m_h = 0.4m_0\). These values have been used by several authors\(^{10-14}\) over a wide range of band gap energies to model the diodes of similar superlattices.

**IV. RESULTS AND DISCUSSIONS**

Measured temperature dependence of \(R_0 A\) of a \(p\)-on-\(n\) SLS diode is shown in Fig. 3 by discrete points. The diode has square shape with area of \(204 \times 204 \mu\text{m}^2\). An estimate of the activation energy from the observed temperature dependence of \(R_0 A\) yields a value of 165 meV, which is approximately \(2/3\) of the band gap. Interestingly it may be noted that Yang et al.\(^{10}\) in their investigations on InAs/(GaIn)Sb superlattice long-wavelength diodes had reported a trap center located in the band gap \((E_g)\) at approximately \(2/3E_g\) above the effective valence band edge. Observation of a similar activation energy in the present case is interpreted here as an indication of a trap level that may be influencing minority carrier lifetime of the SLS material. In other words the lifetime of the minority carriers in the superlattice material of the diodes under study may be limited by SR mechanism. In the absence of the availability of the desired information to calculate the temperature dependence of the SR lifetime in this material, the minority carrier lifetime \(\tau_n\) in this study will be treated as a fitting parameter. Additionally gr lifetime \(\tau_{gr}\) in the depletion region of the diode is also treated as a fitting parameter. The values of these parameters \((\tau_n = 10 \text{ ns} \text{ and } \tau_{gr} = 1.0 \mu\text{s})\) were arrived at by the simultaneous best fit of \(R_{gr} V\) (Fig. 4) and current-voltage (Fig. 5) characteristics of the same diode. Lines in Fig. 3 show the computed temperature dependence of \(R_0 A\) by using these estimated values of minority carrier lifetime and gr lifetime. It is observed that computed diffusion current contribution agrees fairly well with the experimental data in the higher temperature range. Towards lower temperatures deviation of the experimental data from the diffusion line can be well accounted by taking into account the shunt resistance \((5.5 \times 10^7 \Omega)\) of the diode estimated from its dynamic resistance versus reverse bias characteristics to be discussed later. Contribution from gr mechanism is negligible as is evident from the line marked gr.

In the preceding paragraph we have discussed the possibility of the existence of trap levels in the effective band gap of the superlattice material. It will be therefore further inter-
est to explore the contribution from TAT currents, as this trap level was reported\textsuperscript{10} to be contributing to tunneling currents in long-wavelength superlattice diodes. However, since TAT contribution manifests itself at low temperatures, we present here the analysis of reverse bias dynamic resistance $R_{p}^{-}$ characteristics of the diode at the lowest measured temperature of 82 K. As already stated in the beginning, the choice of studying the dynamic resistance characteristics is dictated by the fact that variations in the dynamic resistance of a diode are much more sensitive to the dark current contributing mechanism than the variations in the dark current itself.

Figure 4 shows the measured (discrete points) variation of the dynamic impedance of the diode at 82 K. Lines marked with the respective current components show theoretically calculated contribution of each component after including corrections on account of series and shunt resistances of the diode. The series resistance of the diode is $2.6 \times 10^{3}$ $\Omega$. It can be clearly seen that the forward characteristic of the diode is dominated by thermal diffusion current contribution. In the reverse bias region, diffusion and gr contributions to the dynamic resistance of the diode are practically negligible. The TAT contribution shown in Fig. 4 was calculated by estimating trap density from the peak position of the same characteristics by assuming as if it was caused due to the TAT contribution by the trap levels located at $1/3E_g$ below the effective conduction band edge of SL material. The Ohmic shunt resistance determined from the peak position is $5.5 \times 10^{5}$ $\Omega$. It is observed that the TAT current, which has been previously\textsuperscript{25,26} held responsible for the peak in reverse bias $R_{p}^{-}$ characteristic, is not responsible for the measured characteristic in the present case. Instead it can be clearly seen from Fig. 4 that it is the shunt resistance component of the current that limits the diode performance at low reverse bias voltages near zero bias. Degradation of the dynamic impedance at higher reverse bias voltages is discussed in the following paragraphs along with the discussions on current-voltage characteristics of the diode.

Figure 5 shows a comparison of the measured (discrete points) 82 K current-voltage characteristics with the calculated current (marked lines) components that were used to model the dynamic resistance characteristic of the diode displayed in Fig. 4. It is observed that the thermal diffusion current describes very well the forward characteristic of the diode, but it is smaller by several orders of magnitude compared to the measured current in reverse characteristics. TAT and gr current contributions to the reverse bias current are also negligible. Note that the resultant reverse bias current and the current conducted through the shunt resistance overlap each other in Fig. 5. Thus it is the current conducted through the shunt resistance that dominates the reverse characteristics of the diode. It is suggested that the degradation of the dynamic resistance and a dominant shunt current in the reverse bias are related. It may be recalled here that the dislocations that intersect the junction\textsuperscript{22–24} and/or the surface leakage currents\textsuperscript{15,21} are generally responsible for conducting the Ohmic shunt currents in a diode. Obviously this kind of situation is likely to lead to the current crowding in the localized regions of the base of the diode that may lead to the onset of an early breakdown mechanism such as internal field emission or microplasma avalanche breakdowns. Chynoweth and Pearson\textsuperscript{18} discussed several other reasons as well that may lead to enhancement of electric field around the dislocations, if present. Observation of a degrading dynamic resistance and an excess reverse bias current at higher reverse bias voltages can be thus understood. It should, however, be possible to bring down the Ohmic excess dark currents by making further improvements in the passivation and quality of the basic material used in the fabrication of the diodes.

V. SUMMARY AND CONCLUSIONS

Electrical characteristics of $p$-on-$n$ mid-IR superlattice diode has been modeled by using a bulk based model. It is shown that the thermal diffusion current dominates the forward characteristics of the diode. The reverse bias characteristics are, however, limited by Ohmic shunt resistance contribution. The dominant shunt current in the reverse bias characteristics is also proposed to be responsible for degradation of the dynamic resistance of the diode by the onset of early breakdown mechanisms on account of current crowding that takes place in the localized regions of the base of the diode. Zero-bias resistance area product of the diode is found to be limited by thermal diffusion currents at higher temperatures and Ohmic shunt resistance limits it at low temperatures $\sim$82 K.

ACKNOWLEDGMENTS

This work was supported by DARPA HOT MWIR program. Two of the authors (V. Gopal and S. Krishna) acknowledge the financial support of the Gledden Trust to work as a senior visiting fellow at School of Electrical, Electronic and Computer Engineering, University of Western Australia.

\begin{thebibliography}{18}
\bibitem{15}M. B. Reine, A. K. Sood, and T. J. Tredwell, \textit{Photovoltaic Infrared De-