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Radiation tolerance characterization of dual band InAs/GaSb type-II strain-layer superlattice pBp detectors using 63 MeV protons

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The radiation tolerance characterization of dual band InAs/GaSb type-II strain-layer superlattice pBp detectors of varying size using 63 MeV proton irradiation is presented. The detectors’ mid-wave infrared performance degraded with increasing proton fluence $\Phi_p$ up to $3.75 \times 10^{12} \text{ cm}^{-2}$ or, equivalently, a total ionizing dose $D^*$ of 500 kRad (Si). At this $\Phi_p$, an $\sim 31\%$ drop in quantum efficiency $\eta$, $\sim 2$ order increase in dark current density $J_D$, and consequently, $>1$ order drop in calculated detectivity $D^*$ were observed. Proton damage factors were determined for $\eta$ and $D^*$. Arrhenius-analysis of temperature-dependent $J_D$ measurements reflected significant changes in the activation energies following irradiation. © 2012 American Institute of Physics. [http://dx.doi.org/10.1063/1.4772543]

Infrared (IR) hybrid detector arrays operated in the space environment may be subjected to a variety of radiation sources while in orbit. This means IR detectors intended for applications such as space-based surveillance or space-situational awareness must not only have high performance (high $\eta$ and low $J_D$) but also their radiation tolerance or ability to withstand the effects of the radiation they would expect to encounter in a given orbit must be characterized. As the effects of proton interactions with hybrid detector arrays tend to dominate in space,1 a specific detector’s radiation tolerance is typically characterized by measuring its performance degradation as a function of proton irradiation fluence up to a total ionizing dose (TID) of 300 kRad(Si), which is $2-3 \times$ the maximum expected on-orbit TID value for typical surveillance applications. Radiation tolerance characterization also typically includes determining the rate of performance degradation via a damage factor analysis and, finally, temperature-dependent measurements of $J_D$, which are used to determine the dark current limiting mechanism via an Arrhenius-analysis and the degree to which any thermal annealing of the irradiation induced defects may occur.

Here, the results of a radiation tolerance characterization of dual band InAs/GaSb type II strained layer superlattice (T2SLS) pBp detectors of varying size, which were previously described in Ref. 2, using 63 MeV protons are reported. III-V-based detectors, such as these, are now being considered for space applications due to their relative advantage in manufacturability, compared with conventional mercury-cadmium-telluride (MCT) IR detectors, particularly in the long-wave infrared (LWIR).3 T2SLS detectors are also theoretically predicted to have lower Auger-limited dark currents compared with MCT,4,5 the incumbent technology for high performance space applications. However, this advantage is yet to be realized due to the lack of reliable passivation schemes and relatively higher bulk defect densities in these materials, which lead to surface- and Shockley-Read-Hall (SRH)-limited dark currents, respectively. Unipolar-barrier architecture detectors, including the pBp-detectors reported here, were recently introduced in an effort to mitigate these dark current limiting mechanisms.6–8 By deliberate choices of the growth materials and wafer structure, the potential barriers in these detectors appear only in either the conduction or valence band to block the majority-carrier bulk and surface currents (e.g., in a pBp detector, the potential barrier appears only in the valence band). Simultaneously, the barrier layer ideally limits the depletion by an external bias to itself so the absorbing layer remains in the flatband condition, which eliminates GR-currents from whatever defects may be present in the absorbing layer.

Subjecting IR detectors to proton irradiation is expected to lead to both TID and displacement damage effects, both of which occur on orbit. TID effects occur as incoming protons lose their kinetic energy to ionization of the detector material’s constituent atoms and the additional charges become trapped in oxide layers or surface traps. This additional charging may result in flat-band voltage shifts and increased surface leakage currents. TID effects generally are more visible at lower device temperatures, where charges generated in oxide layers are less mobile, and tend to anneal out at higher temperatures. Displacement damage effects result from the occasional non-ionizing energy loss of an incoming proton due to elastic or inelastic scattering with an atomic nucleus that is sufficient to knock the atom from its lattice site and generate vacancy-interstitial pair, anti-sites, and defect complexes.9 These defects may manifest in lower $\eta$, due to the consequent reduction in minority carrier lifetime $\tau$, and higher $J_D$, due to the SRH mechanism. The proton fluence at 63 MeV required to alter the background doping levels, such that the fundamental Auger mechanism is enhanced, is expected to be order’s higher than the fluence levels used here. Thus, the first step to characterizing a detector’s radiation tolerance is measuring $\eta$ and $J_D$ as a function of $\Phi_p$, with all irradiation and measurements conducted at the detector’s expected operating temperature and bias. The importance of the latter is vividly illustrated by

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recent preliminary 1–2 MeV proton irradiation studies of Sb-based T2SLS photodiodes where the detectors were unbiased and at 300 K during irradiation, which presumably precluded observing the effects of ionization and lower energy defects due to displacement damage, both of which were expected to anneal at room temperature.\textsuperscript{10,11} Thermal annealing of radiation effects at 300 K was shown in Ref. 1 and was likewise observed during this experiment on the T2SLS detectors. Using $\eta$ and $J_B$ to also estimate the detector sensitivity, expressed here in this letter by shot-noise-limited $D^*$, is then done to illustrate which of the two dominates the change in overall performance.

Radiation tolerance can be further characterized by calculating the damage factor $K_X$ or the rate of degradation for each performance metric $X$ (e.g., $X = \eta, J_B, D^*$, etc.) from the performance measurements taken versus fluence. For comparison purposes, however, it is worth noting that these $K_X$-metrics may be a function of a detector’s architecture, material composition, growth method, processing, passivation, etc., and are thus entirely specific to that particular detector. $K_X$’s are also specific to the particle type and energy of the irradiation. In fact, with a known energy-dependence of the expected on-orbit degradation $\Delta X$ ideally become possible, according to $\Delta X = \int_{E_1}^{E_2} K_X(E) \frac{\partial \Phi_p}{\partial E} dE$, where $\frac{\partial \Phi_p}{\partial E}$ is an expected orbit’s differential proton fluence spectrum.\textsuperscript{1}

Temperature-dependent measurements of $J_D$ at the expected operating bias are also used to characterize the effects of proton irradiation on IR detectors. Determining the activation energy, $E_A$, via an Arrhenius-type analysis of the $J_D$-measurements allows for changes in the limiting mechanism of $J_D$ at specific temperatures to be discerned if it is done prior to and immediately following irradiation. These are henceforth referred to as the pre-rad and post-rad conditions, respectively. As the post-rad detector is warmed up to room temperature, it is also often the case that some degree of thermal annealing of the irradiation induced defects will occur. Thus, a third set of temperature-dependent $J_D$-measurements is typically performed after this initial warm-up, henceforth referred to as the post-anneal condition, to characterize the effects of any thermal annealing. A standard $\eta$ and $J_D$-measurement at the expected operating conditions are also usually performed post-anneal.

The dual-band, InAs/GaSb T2SLS pBp detectors used in this study were previously fully described in Ref. 2. Summarizing those details, the pBp detectors are grown via molecular beam epitaxy on GaSb substrate material and include two 2 $\mu$m, p-type, Be-doped $\sim 1 \times 10^{16}$ cm$^{-3}$, InAs/GaSb SLS absorbing layers designed for mid-wave infrared (MWIR) and LWIR response that are separated by a similarly doped InAs/AlSb barrier layer. Samples with square mesa devices varying in mesa edge length $L$ from 45 to 145 $\mu$m and etched through both absorber layers to the bottom contact layer were then fabricated from the material by standard photolithography and wet-etching processes and then wirebonded to 68 pin leadless chip carriers for cryogenic testing purposes. FTIR absorption measurements at forward- and reverse-bias showed the zero-response cutoff wavelength $\lambda_c$ in the MWIR and LWIR were 7.8 and 12 $\mu$m at 80 K, respectively. However, only the MWIR optical results are discussed in this letter as the low LWIR signal level prevented a completely reliable radiation tolerance characterization for that band.

The proton irradiation was performed at the Crocker Nuclear Laboratory at the University of California, Davis, using their 76" isochronous cyclotron, which can provide protons with energies up to 68 MeV.\textsuperscript{12} The detectors were at their nominal operating conditions, biased at $V_B = +0.1$ V and $T = 80$ K, during proton irradiation. Photocurrent and dark current measurements were performed on $L = 45, 65, 85$, and 145 $\mu$m mesa devices at TID = 0, 2, 5, 10, 20, 50, 100, 200, and 500 kRad(Si), as well as following a post-rad, 2 day, 300 K thermal anneal.

Photocurrent measurements were taken with the detectors held at the MWIR operating bias, $V_B = +0.1$ V applied to the top of each mesa, using standard ac lock-in technique at $f/\pi \approx 40$ and a blackbody source at $T_BB = 900$ K. The blackbody output was passed through a room-temperature 3.5–4.2 $\mu$m IR band-pass filter and a KRS5 dewar window, followed by a 4 mm pinhole held at 77 K within the dewar, leading to an incident photon flux $E_Q = 3.1 \times 10^{14}$ ph/s/cm$^2$ at peak wavelength $\lambda_p \approx 3.9$ $\mu$m. For mesa detectors, the photocurrent is given by $I_p = q \eta E_Q L^2$, where $q$ is the charge of an electron. Thus, $\sqrt{I_p}$ was plotted as a function of $L$ and a weighted, least squares linear fitting was performed. The fitting’s slope parameter $m$ was then used to determine $\eta$ according to the expression $\eta = m^2/qE_Q$.

Dark current measurements were then performed using a standard dc source-measurement unit with a 77 K shutter blocking the pinhole. As it is typically more sensitive to irradiation, dark current was always measured following the $I_{photo}$ measurements, to allow for any transient effects to fully diminish. Finally, temperature-dependent measurements of $J_D$ were performed from $T = 77$ K to 300 K at the MWIR operating bias $V_B = +0.1$ V and an Arrhenius-analysis was performed to determine $E_A$ and thus, gain some insight regarding the dark current limiting mechanism.

Measurements of the detector’s $\eta$ at $\lambda_p \approx 3.9$ $\mu$m, derived from the $I_p$-measurements, as function of $\Phi_p$ and post-anneal are shown in Fig. 1. In the pre-rad condition, as Fig. 1 shows,
\( \eta \sim 29\% \), which roughly matches the result given in Ref. 10. The \( \eta \) was then observed to degrade roughly linearly with increasing \( \Phi_p \) to \( \sim 21\% \) at \( 3.75 \times 10^{12} \text{ cm}^{-2} \) or, equivalently, TID = 500 kRad(Si), a 28% change in \( \eta \). From the slope of the data in Fig. 1, the MWIR \( \eta \) damage factor was found to be \( K_\eta = -2.14 \times 10^{-14} \text{ e-cm}^2/\text{ph-H}^+ \). Following irradiation, the detector temperature was raised to 290 K for \( \sim 48 \) h and then re-measured, whereby \( \eta \) recovered to \( \sim 28\% \). As proton irradiation is known to generate bulk defects, and thereby reduce \( \tau \) and diffusion length \( L_D \propto \sqrt{\tau} \), the drop in \( \eta \) in Fig. 1 suggests \( \eta \propto 1 - e^{-\kappa \phi} \), where \( \kappa \) is the absorption coefficient and \( L_0 < 2 \mu \text{m} \), the thickness of the MWIR absorbing layer, since \( \kappa \) is not expected to change with fluence. A perimeter-to-area (P/A) analysis of these results, which suggests some surface-related recombination is also occurring, will be discussed in a forthcoming publication.13

Measurements of \( J_D \) at \( V_B = +0.1 \) V as a function of \( \Phi_p \) and post-anneal for each detector are shown in Fig. 2, while the inset shows the measured I-V relationship for the 45 \( \mu \text{m} \) device under similar conditions. These results all show a monotonic increase in \( J_D \) with increasing \( \Phi_p \), up to \( 3.75 \times 10^{12} \text{ cm}^{-2} \), at which point a roughly two order increase in \( J_D \) was observed. For \( \Phi_p < 10^{12} \text{ cm}^{-2} \), however, the rate of increase of \( J_D \) appears to depend on \( L \), which is indicative of surface currents. A perimeter-to-area analysis of \( J_D \) to investigate the surface current effect will also be discussed in the other forthcoming publication.13 For \( \Phi_p > 10^{12} \text{ cm}^{-2} \), the change in \( J_D \) appears to saturate slightly; however, this effect requires more investigation and may be transient. Following irradiation, two consecutive thermal anneals, at 240 K for 2 h and at 300 K for 48 h, were conducted. Following each an \( \sim 25\% \) and \( \sim 50\% \) reduction in irradiation induced \( J_D \) were observed.

To approximate the expected reduction in sensitivity with increasing \( \Phi_p \), the shot-noise limited \( D^* \) for the 45 \( \mu \text{m} \) detector was then calculated from the results in Figs. 1 and 2 using the expression \( D^* = R / \sqrt{2(2qI + (4k_B T) / R_d A_d)} \), where \( R = \eta \lambda / (hc / \eta p) \) is the detector responsivity, \( k_B \) is Boltzmann’s constant, \( R_d \) is differential resistance, \( A_d \) is the detector area, \( h \) is Planck’s constant, and \( c \) is the speed of light. While this method of calculating \( D^* \) is often of limited utility in accurately describing the detector’s sensitivity, due to the omission of additional noise sources as described in Ref. 14, as it is used here it serves as a good means of estimating the sensitivity’s dependence on \( \Phi_p \). A plot of \( D^* \), again as function of \( \Phi_p \) and post-anneal, is given in Fig. 3. Here, \( D^* \) is predicted to degrade over an order of magnitude from its pre-rad value of \( 4.86 \times 10^{10} \text{ cmHz}^{1/2}/\text{W} \) down to \( 2.12 \times 10^9 \text{ cmHz}^{1/2}/\text{W} \) in post-rad. Fig. 3 also includes plots of \( D^* \) calculated with either \( \eta \) or \( J_D \) held fixed at its pre-rad value. These two plots show that the dependence of \( D^* \) on \( \Phi_p \) is completely dominated by changes in \( J_D \). Post-anneal, only a 49% drop in \( D^* \) is calculated compared to the pre-rad condition. For \( \Phi_p < 10^{12} \text{ cm}^{-2} \), a \( D^* \) damage factor \( K_{D^*} \sim 4.53 \times 10^{-2} \text{ cm}^3/\text{Hz}^{1/2}/\text{W-H}^+ \) was determined.

Three sets of temperature-dependent \( J_D \)-measurements, reflecting the pre-rad, post-rad, and post-anneal conditions, for the 45 \( \mu \text{m} \) mesa detector at \( V_B = +0.1 \) V are shown in Fig. 4. Here, the pre-rad and post-anneal results clearly show two distinct regions of \( T \)-dependence, with crossovers at \( T = 115 \) K and 93 K, respectively, while for the post-rad data this is much less clear. From the Arrhenius-analysis of the pre-rad and post-anneal plots in Fig. 4, an \( E_A \sim 155 \) meV was extracted for the high-\( T \) region, which directly corresponds to the measured \( \lambda_c \sim 8.1 \mu \text{m} \) for this device and indicates diffusion-limited \( J_D \) in this region. In the low-\( T \) region, slightly different \( E_A < E_{g0}/2 \) and amplitudes were determined for the pre-rad and post-anneal data. These differences suggest \( J_D \) is SRH-limited with additional irradiation-induced defects that remained non-annealed affecting the post-anneal data. The post-rad \( J_D \) data had an \( E_A \) as low as 20 meV up to \( T = 115 \) K and slowly increasing until \( T \sim 175 \) K, when it begins to show a similar high-\( T \) dependence as the other traces, presumably due to the combined effects of thermal annealing and enhancement of the diffusion-limited \( J_D \) with \( T \). The low \( E_A \) and high amplitude for the post-rad \( J_D \) at \( T < 175 \) K, in comparison with the other traces, most likely reflects surface-limited behavior.

\[ D^* = R / \sqrt{2(2qI + (4k_B T) / R_d A_d)} \]

FIG. 2. \( J_D \) measured for the \( L = 45, 65, 85, \) and 145 \( \mu \text{m} \) detectors at \( \Phi_p \) ranging from 0 to \( 3.75 \times 10^{12} \text{ cm}^{-2} \) and post-anneal. Inset: I-V relationship for 45 \( \mu \text{m} \) detector in pre-rad, post-rad, and post-anneal conditions.

FIG. 3. Shot-noise limited \( D^* \) (black squares) for 45 \( \mu \text{m} \) mesa detector with \( \Phi_p \) ranging from 0 to \( 3.75 \times 10^{12} \text{ cm}^{-2} \) and post-anneal and with \( \eta \) (red circles) and \( J_D \) (green triangles) fixed to its pre-rad values. The linear fitting had a slope of \( K_{D^*} \sim 4.53 \times 10^{-2} \text{ cm}^3/\text{Hz}^{1/2}/\text{W-H}^+ \).
stemming from TID effects as the dark current nearly recovers to its pre-rad value following the 300 K thermal anneal.

In conclusion, a radiation tolerance characterization of a pBp detector employing a T2SLS absorber was performed using 63 MeV proton irradiation. Measurements of $\eta$ and $J_D$ reflected a degradation of the detector performance with increasing $\Phi_p$ that would necessarily result in a larger increase in near mid-gap defect density post-rad (post-anneal).

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