Ultraslow Dynamic Annealing of Neutron-induced Defects in n-type Silicon

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Neutron bombardments with equivalent fluence \((1 \times 10^{10} \text{ cm}^{-2})\) and different fluxes have been performed on one kind of bipolar transistor and two kinds of bipolar circuits. The base currents or input bias currents of almost all samples are found to decrease with increasing neutron flux, implying that the strength of the dynamic annealing of divacancy defects \((V_2^-)\) in n-type silicon follows a positive flux dependence. Such flux dependence is the same as that observed in ions implantation using protons, boron, carbon, and other heavy ions, but the transition flux in our experiment \((\sim 1 \times 10^6 \text{ cm}^{-2}\text{s}^{-1})\) is 4 orders of magnitudes lower than that of proton bombardment, despite the similarity in the masses and energies of the two particles. A new model considering dissipation of diffused Si interstitials was proposed for the flux effect, in which the huge discrepancy in transition fluxes is attributed to the presence of vast charge carriers in proton bombardments, which strongly accelerate the dynamic annealing of defects by enhancing the diffusion velocity of Si interstitials. Our work would contribute to the understanding of the defect buildup processes in silicon.

I. INTRODUCTION

Bombardment of energetic particles induce atomic displacements and structural defects in crystalline semiconductors. The population of the created stable defects depends on the process of the defects’ generation as well as their thermal and dynamic annealing during the bombardments. Factors of crucial importance for damage buildup in semiconductors are the energy, mass, fluence, and flux of the incident particles, as well as the temperature of the samples. Interestingly, the dependence of dynamic annealing on the fluence and flux show non-trivial characteristics. For the experiments of total fluence exceeding \(1 \times 10^{12} \text{ cm}^{-2}\) and flux in the range of \(1 \times 10^{10} - 1 \times 10^{15} \text{ cm}^{-2}\text{s}^{-1}\), it is well recognized that, the strength of the dynamic annealing of defects decreases with increasing flux \([4]\). The mechanism is explained as follows: At sufficiently high flux, collision cascades can overlap before a single defect cascade can complete its annealing process; as a result, a higher concentration of defects which are more stable at (and above) room temperature is formed \([5]\). However, for experiments of low total fluence of about \(5 \times 10^9 \text{ cm}^{-2}\) and low flux in the range of \(1 \times 10^7 - 2 \times 10^{10} \text{ cm}^{-2}\text{s}^{-1}\), a reverse positive flux dependence of dynamic annealing is found in silicon bombarded by ions including proton \([6, 8]\), \(^{6}\text{He}\) \([8]\), \(^{11}\text{B}\), \(^{12}\text{C}\), \(^{16}\text{O}\), \(^{28}\text{Si}\), \(^{74}\text{Ge}\), \(^{76}\text{Ge}\), and \(^{120}\text{Sn}\) \([9, 11]\). In these experiments, the concentrations of the induced defects (such as \(V_2^-, \text{VO, } V_2^0\), and hydrogen-related defects) show the most sensitive dependence on the flux at certain flux, which can be defined as a transition flux. It is remarkable that, the transition flux becomes smaller for ions of heavier mass or larger energy \([11]\). For example, proton with the smallest mass shows the biggest transition flux \((\sim 1 \times 10^{10} \text{ cm}^{-2}\text{s}^{-1})\), while \(^{120}\text{Sn}\) with the biggest mass displays the smallest transition flux \((\sim 2 \times 10^9 \text{ cm}^{-2}\text{s}^{-1})\).

It should be noticed that, the incoming ions induce both non-ionizing and ionizing energy dispositions in semiconductors, which are measured by the non-ionizing energy loss (NIEL) and ionization energy loss (IEL), respectively. For 1MeV protons, NIEL is \(6.38 \times 10^{-2}\text{MeV cm}^{-3}/\text{g}\) and IEL is \(1.71 \times 10^2\text{MeV cm}^{-3}/\text{g}\). The ratio between them is over 2.6 \(\times 10^3\). Other ions also possess large potions of IEL in the total deposition energy. It is well-known that, NIEL directly contributes to the construction of the displacement defects, while IEL generates electron-hole pairs. Previous research \([12–15]\) of injection annealing has identified that the presence of charge carriers can strongly enhance the dynamic annealing processes. The origin comes from the enhanced mobility of isolated Si interstitials through alternating capture and lose of electrons \([16–20]\). The IEL in the ion bombardments may generate higher concentrations of charge carriers than the injection, hence can more efficiently promoted the dynamic annealing. How will the dynamic annealing behave like if the vast background charge carriers were removed? Will the positive flux dependence still hold? To answer these interesting questions will not only be helpful to reveal the basic mechanism of the dynamic annealing but also be helpful to clarify the role of charge carriers in the defect buildup. However, to our best knowledge, there is rarely such investigation.

In this work, we investigate the flux dependence of the dynamic annealing in n-type silicon by neutron bombardment of PNP transistors. The neutrons are used instead of protons or other ions because they have much smaller IEL/NIEL ratio (\(\sim 0.82\)); the transistors are used instead of bulk silicon because the recombination base currents are very sensitivity to the low concentration defects. Equivalent fluence \((1 \times 10^{10}\text{cm}^{-2})\) neutron bombardments of PNP transistors and operational amplifiers...
are carried out in the flux range between $5 \times 10^5$ cm$^{-2}$s$^{-1}$ and $5 \times 10^6$ cm$^{-2}$s$^{-1}$ at room temperature. The base currents and input bias currents are found to decrease with increasing flux, which means a positive flux dependence of dynamic annealing as same as the proton and other ions cases. Remarkably, we find that the transition flux ($\sim 1 \times 10^6$cm$^{-2}$s$^{-1}$) induced by neutron bombardment is nearly 4 order of magnitudes lower than that induced by proton bombardment, which we attribute to a prominent influence of charge carriers on the defects evolutions. We also analysis the existing model for the positive flux dependence and propose a new mechanism considering dissipation of rapidly diffused Si interstitials.

II. EXPERIMENTAL SETUP

To investigate the flux dependence of dynamic annealing in absence of charge carriers, neutron is used instead of protons. Neutrons have much smaller IEL/NIEL ratio ($\sim 0.82$) with IEL of 1.67 $\times$ 10$^{-3}$MeV-cm$^{-3}$/g and NIEL of 2.04 $\times$ 10$^{-3}$MeV-cm$^{-3}$/g. In this configuration, the possible influence of charge carriers can be reduced to the lowest level. Neutron bombardments were performed at the Chinese Fast Burst Reactor- II (CFBR-II) of Institute of Nuclear Physics and Chemistry, China Academy of Engineering Physics, which provides controlled 1MeV equivalent neutron bombardment. The energy is similar to that (1.3MeV) of the protons in the previous experiment [7]. The total fluence is choosen as $1 \times 10^{10}$cm$^{-2}$, which is similar to the fluence used in previous experiments of protons and other ions [7–11]. Considering the difference of IEL/NIEL ratios, the neutron flux is set from $5 \times 10^5$ cm$^{-2}$s$^{-1}$ to $5 \times 10^6$ cm$^{-2}$s$^{-1}$.

The type of the induced defect is characterized by the widely-used deep level transient spectroscopy (DLTS) technology [21, 22]. Defects of $p^+/n$ diodes were measured using PhysTech Fourier Transform DLTS system equipped with a liquid nitrogen cryostat. The capacitance transients (ΔC) were measured with a 1 MHz DLTS spectrometer operated with a temperature scan from 77K to 300K. The applied reverse bias voltage ($V_R$) and filling pulse voltage ($V_F$) were -10 V and -0.5 V, respectively. Data presented here were taken with a rate window of 204.8 ms and the filling pulse width $t_F$ of 10 ms. For bulk silicon we found that defects cannot be detected until the neutron fluence exceeds $1 \times 10^{12}$cm$^{-2}$.

To detect the defects generated by $1 \times 10^{10}$ cm$^{-2}$ fluence neutrons, recombination base current of bipolar transistors are used instead. To enlarge the universality of the results, commercial operational amplifier (Op-amp) including with PNP input-stage transistor are also selected as research objects. The widely used Op-amp LM324N and LM124 are used; for both the input stage are very straightforward and the input bias current is directly related to the concentration of defects in the n-
type silicon of the input-stage PNP transistors $^{23, 24}$. For PNP transistors, the base currents ($I_B$) are measure by Keithley 4200. For Op-amps, the input bias currents ($I_{IB}$) are measured by simi3193 discrete semiconductor testing systems.

PNP transistors were separated into 3 splits and bombarded at fluxes of $5 \times 10^5$ cm$^{-2}$s$^{-1}$, $1 \times 10^6$ cm$^{-2}$s$^{-1}$, and $2.5 \times 10^6$ cm$^{-2}$s$^{-1}$, respectively. During the measurements, the emitter is grounded while the collector and base voltage is scanned from 0 V to $-1$ V. The base current is recorded at $-0.6$ V. LM324N were separated into 5 splits and bombarded at fluxes of $5 \times 10^5$ cm$^{-2}$s$^{-1}$, $8 \times 10^5$ cm$^{-2}$s$^{-1}$, $1 \times 10^6$ cm$^{-2}$s$^{-1}$, $2.5 \times 10^6$ cm$^{-2}$s$^{-1}$, $5 \times 10^6$ cm$^{-2}$s$^{-1}$, respectively. LM124 were separated into 3 splits and bombarded at fluxes of $5 \times 10^5$ cm$^{-2}$s$^{-1}$, $8 \times 10^5$ cm$^{-2}$s$^{-1}$, and $5 \times 10^6$ cm$^{-2}$s$^{-1}$, respectively. During the bombadments, all pins are shorted and grounded. During the measurements, both Op-amps are placed in an open loop configuration.

III. RESULTS AND DISCUSSION

A. FLUX DEPENDENCE OF INPUT BASE CURRENTS AND DYNAMIC ANNEALING IN BIPOLAR CIRCUITS

The results of LM324N are plotted in Fig. 2. For each tested flux point, the population of the samples are 20, 20, 12, and 20, respectively. At low fluence, the generated defects are very few; the changes of $I_{IB}$ may be overwhelmed by the sample-to-sample variability $^{25}$. To avoid this confusion, the discrete results of each sample is plotted instead of the average of the results. The informations obtained from the figures are as follows. First, the initial input bias currents distribute randomly within a range of 1-3nA for each flux condition, which can come from many sources $^{25}$. Secondly, for almost all samples in each split, the input bias currents become larger after neutron bombardments. To gain a clearer description, in Fig. 2 we plot the increased input bias currents as a function of the pre-bombardment values. It is clear that although the initial values are different, the responses to a certain fluence are similar. In other words, the data show no clear correlation with the initial $I_{IB}$. As suggested by $^{26}$, this fact reflects that the damage is mainly generated in the neutral base region. Thirdly and most importantly, $\Delta I_{IB}$ shows clear flux dependence. From Fig. 2, it is seen that the neutron-induced net increment of input bias currents decrease with increasing flux for a fixed total fluence. For examples, at the flux of $5 \times 10^5$ cm$^{-2}$s$^{-1}$, $\Delta I_{IB}$s are approximately equal to 1.35nA. For the flux of $5 \times 10^6$ cm$^{-2}$s$^{-1}$, $\Delta I_{IB}$s are approximately equal to 0.33nA. More intuitional plots of the dependence of $\Delta I_{IB}$ on neutron flux are shown in Fig. 3 as the red curve. Seen from the figure, in the flux range of the experiments, $\Delta I_{IB}$s are likely to show linear dependence on the log of the flux. The relationship can be expressed by

$$\Delta I_{IB} \propto -k \times \log(\text{flux}),$$

where $k$ is the gradient per order of magnitudes; for LM324N it reads 4.2. The input bias current is a direct reflection of the concentration of generated defects in the neutral base region of the input-stage PNP transistor. The flux dependence of the bias input current implies a similar dependence of the defect concentration in n-type silicon. Correspondingly, the strength of the dynamic annealing increases with increasing neutron flux. This flux dependence is the same as the results obtained from proton and other ions bombardments $^{27}$. From the figure, the transition flux is $\sim 1 \times 10^6$ cm$^{-2}$s$^{-1}$, which is 4 orders of magnitude lower than the transition flux.
of proton bombardment. Considering that neutron and proton have very similar masses and energies, this is a very remarkable result.

Is the observed rule general? To answer this question, the same analysis have been made on another bipolar circuit LM124. Results similar to Fig. 1 has been obtained. The increment of the input bias currents as a function of proton bombardment \( I_{0,B} \) are plotted in Fig. 4. From Fig. 4 we can see that, the initial input bias currents distribute randomly in a range of 2nA-4nA. Similar to LM324N, \( \Delta I_{B} \) decreases for increasing flux. The averages of \( \Delta I_{B} \) are plotted in Fig. 5 by blue curve, which, similar to LM324N, also shows a linear shape with a smaller gradient of \( k = 1.8 \). This means a positive flux dependence of the dynamic annealing. Remarkably, the transition flux is also at \( \sim 1 \times 10^{8} \text{cm}^{-2}\text{s}^{-1} \), implying the universality of the flux dependence.

\[
\Delta I_{B} \propto \sum j_{th}^{-1} = \sum \sigma_{j} v_{th} N_{j} ,
\]

where \( j \) represents the species of the defects, \( \sigma_{j} \) is the capture cross-section of minority carriers, \( v_{th} \) is the thermal velocity of minority carriers, and \( N_{j} \) is the concentration of the defects. The base current is mainly contributed by the defects that produce energy levels in the middle third of the Si band gap.

For proton bombardment of n-type silicon [7], five peaks of activation enthalpies of \( E_{1}=0.17\text{eV}, E_{2}=0.23\text{eV}, E_{3}=0.32\text{eV}, E_{4}=0.43\text{eV}, \) and \( E_{5}=0.45\text{eV} \) are found in the DLTS spectrum, from which defects of VO (\( E_{1} \), \( V_{2}^{<} \) (\( E_{2} \)), \( V_{2}^{>} \) (\( E_{3} \)), and hydrogen related defects (\( E_{3,5} \)) are identified [22, 32, 43]. For neutron bombardment, the DLTS test on \( p^{+}-n \) diodes made using the same processes as the PNP transistors show only \( E_{1} \) (VO defect) and \( E_{4} \) (\( V_{2}^{>} \) defect), see Fig. 4. The energy level of \( V_{2}^{<} \) lies in the middle third of the Si band gap. Neither \( \sigma \) nor \( v_{th} \) of \( V_{2}^{<} \) changes during the bombardment, therefore the measured flux dependent behavior of \( \Delta I_{B} \) reflects directly the flux dependence of the \( V_{2}^{<} \) defects. It is clear that the dynamic annealing of \( V_{2}^{<} \) becomes strong for increasing neutron flux. The transition flux is 4 order of magnitudes lower than that in the proton bombardment. From Fig. 4 it is also seen that the defects cannot be detected until the fluence exceeds \( 1 \times 10^{12}\text{cm}^{-2} \), which is 100 times larger than the concerned fluence. That’s the reason why we use the base current of a PNP transistor as a probe of the ultra-low concentration defects in n-type silicon.

**B. FLUX DEPENDENCE OF BASE CURRENTS AND DYNAMIC ANNEALING IN BIPOLAR TRANSISTORS**

The flux dependent behavior of the base currents of a lateral PNP transistor is further investigated. The obtained data show similar behaviors as those in Fig. 1 and 4. The dependence of the average \( \Delta I_{B} \) on neutron flux is plotted in Fig. 5 as the green curve. It is seen that, \( \Delta I_{B} \) decrease monotonously with the increase of the flux. Both the gradient and transition flux are similar to those of the two bipolar circuits. This fact further supports the equivalency between the input bias current of the circuits and the base current of the input-stage transistors [23, 24]. The increment of the base current stems from the increment of defects in the neutral base region which decrease the lifetime of minority carrier (\( \tau \)) [27, 37].
C. MECHANISMS FOR FLUX EFFECT AND DISCREPANCY IN TRANSITION FLUXES

The positive flux dependence of dynamic annealing (in presence of vast charge carriers) was attributed to the recombination between rapidly diffusing silicon self-interstitials in one ion track and (also movable) vacancies (V) created in adjacent ion tracks. It was proposed that at low flux, the vacancies have enough time to diffuse and form stable defects, leaving diluted simple vacancies which reduces the efficiency of the annihilation with interstitials from later ions. While at high flux, the vacancies created by one ion are still confined to a small volume when interstitials from later ions come, which enhance the annihilation efficiency. However, we don’t think the dense or diluted vacancy-related defects would cause any differences to the total capabilities of the annihilation. This is because the total amounts of the defects in the interested region are the same. Further, based on this model, neutron and proton bombardments would result in very similar transition fluxes, as the mass of neutron and proton are almost the same. Hence, the huge difference up to 10,000 times in the transition fluxes cannot be reasonably explained based on this model.

In this work, we favor a new mechanism based on the dissipation of rapidly diffusing Si interstitials. The schematic illustration of the mechanism is shown in Fig. 6. After a damage cascade is generated, the interstitials and vacancies start to recombine through intra-cascade recombinations, which are flux independent. Besides, the vacancies are forming more stable vacancy-related defects (V_{2}^{−}, VO, V_{2}^{2−}, etc.) while the mobile interstitials would leave the cascade and rapidly diffuse through the sample. The key is that the rapidly diffusing interstitials can disappear by interface absorption, re-merging into the lattice, or interacting with the impurities. For high enough flux, a subsequent damage cascade can be generated before a large portion of interstitials have dissipated out of the systems (see, Fig. 6a). As a result, the diffusing interstitials would have decent possibility to recombine with the vacancy-related defects of the second cascade. In contrast, at low flux, most interstitials have dissipated before the subsequent cascade is generated (see, Fig. 6b). As a result, the inter-cascade recombinations would be weak. Therefore, the higher flux bombardment would lead to an enhanced annealing of the vacancy-related defects which leads to the reduced defects buildup. It is clear that, in this model the diffusion speed of the interstitials is a characteristic parameter limiting the transition flux. For proton bombardment, the interstitials diffuse much faster due to the presence of IEL-induced charge carriers. This is the reason for a much shorter time (higher transition flux) of the dynamic annealing.

IV. CONCLUSION

To investigate the flux dependence of dynamic annealing of displacement defects in absence of charge carriers, neutron bombardment of equivalent fluence and different fluxes have been performed on bipolar transistors and circuits, whose ultra sensitivity recombination currents provide a probe for the concentration of very few V_{2}^{−} defects in silicon. Similar to proton bombardment, the defect concentration (strength of dynamic annealing) is found to decrease (increase) with increasing neutron flux. However, the transition flux (∼ 1 × 10^{6} cm^{−2}s^{−1}) is about 4 orders of magnitude lower, despite of similar mass and energy of the two particles. The huge discrepancy is attributed to IEL-induced large difference in diffusion velocity of Si interstitials in a new model considering the dissipation of diffusing Si interstitials. The obtained effect and unraveled mechanisms will be helpful for the study of the basic process of dynamic annealing and the role of IEL in it.

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