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Numerical Analysis of Correlation between UV Irradiation and Current Injection on Bipolar Degradation in PiN Diodes

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Abstract. We have proposed an E-V-C (Expansion-Visualization-Contraction) method by using UV irradiation, for screening potential defects which causes reliability issue called bipolar degradation in 4H-SiC devices. This method is based on the property that the REDG (recombination-enhanced dislocation glide) mechanism causing the bipolar degradation can be reproduced by UV irradiation. However, in order to apply this method as a screening, accurate quantification of the correlation between current density in forward bias and UV irradiance is required. This article describes how to set UV irradiation conditions (irradiance and irradiation time) to simulate forward biased current conditions.

Introduction

As part of efforts to curb CO_2 emissions to prevent global warming, the expansion of renewable energy sources such as solar and wind power generation, as well as the electrification of automobiles such as HEVs and EVs, is being promoted at a rapid pace on a global scale. Power semiconductors, which are the basic elements that make up these technologies, are the driving force behind their realization, and currently more than 95% of their base materials are made of silicon (Si). However, Si is beginning to show its limitation of device performance coming from the limitation of the material constant, and new materials such as SiC (silicon carbide), GaN (gallium nitride), and Ga_2O_3 (gallium oxide), which excel in high breakdown voltage, low loss, high-frequency operation, and high temperature operation, are drawing attention. Among these, SiC is currently attracting the most attention for its functionality, reliability, and ease of mass production, with the aim of expanding its mass production. However, the 4H-SiC devices currently widely used in products have been found to have a reliability issue called bipolar degradation. This degradation is caused by the nucleation and expansion of single Shockley stacking faults (1SSFs) derived from line defects called basal plane dislocations (BPDs) in the epilayer or near the epilayer/substrate interface. The 1SSF expansion is explained by the REDG mechanism in which excess minority carriers injected into the BPD region are expanded by the recombination energy of electrons and holes. Various process improvements have been made to convert BPDs to benign dislocation TEDs (threading edge dislocations) at the epilayer/substrate interface, which does not expand. However, it is known that at high current densities, expansion occurs from the BPD-to-TED conversion point, and the issue has not yet been fully resolved.

So far, in some device manufacturers so-called "burn-in" screening is performed, in which the bipolar degradation is checked, chip by chip, by applying accelerated current stress for a certain period. This is a very time-consuming process which raises a total cost of production. In order to replace the time-consuming “burn-in” screening, we have proposed the E-V-C method as a means of screening out TED-converted BPDs [1]. The E-V-C method is a technique to visualize and screen TED-converted BPDs by utilizing UV irradiation and PL observation. In order to make the use of UV irradiation to be useful and practical as a screening method, it is required that the UV irradiation conditions must match the specifications of each product, specifically, the absolute maximum current rating of the product. This is because, if UV irradiance is unnecessarily intense, even devices that would not show any degradation within the rated current in normal usage will be screened out (overkill). Therefore, it is essential to derive an accurate quantitative correlation between forward bias condition and UV irradiation condition to avoid overkill situation. It is relatively easy to experimentally derive the correlation if it is only for one specific wafer. The authors' team has reported the quantitative derivation of the correlation for PiN diodes fabricated on a single 4” wafer [2]. However, in order to make the correlation to be more general and versatile, the correlation should be formulated physical theory based. In this article, the correlation between forward bias and UV irradiation is derived in terms of intensity (current density and irradiance) and time (current flowing time and irradiation time) based on physical model.

UV Irradiance Determination (Equal Hole Density at Drift/Buffer Interface)

It has been reported that the expansion of a TED-converted BPD depends on whether the hole density near the conversion point exceeds a certain threshold or not [3]. That is, the key indicator bridging forward bias and UV irradiation is the hole density near the BPD-to-TED conversion point. Taking PiN diodes as an example, since most BPDs are converted near the i/n+(drift/buffer) interface, the UV irradiation conditions should be so determined that the hole density at the i/n+ interface becomes the same between UV irradiation and forward bias. When the current flow is constant, the hole density does not change over time, meaning in a steady state. The spatial distribution of hole density $\Delta p_{FB}(x)$ inside the i-layer during high current injection is given by Eq. 1 [4].

$$\Delta p_{FB}(x) = \frac{J\eta_i\tau_i}{2qL_a}\left[\frac{\cosh\left\{\left(x-\frac{W}{2}\right)/L_a\right\}}{\sinh\left\{\left(\frac{W}{2}\right)/L_a\right\}} - B'\frac{\sinh\left\{\left(x-\frac{W}{2}\right)/L_a\right\}}{\cosh\left\{\left(\frac{W}{2}\right)/L_a\right\}}\right]. \tag{1}$$

$where\ x: distance\ from\ p+/drift\ interface,\quad J: current\ density$
$\eta_i: recombination\ current\ density\ ratio\ in\ drift\ layer$
$\tau_i: carrier\ lifetime\ in\ drift\ layer,\quad W: drift\ layer\ thickness$
$L_a: ambipolar\ diffusion\ length,\quad q: elementary\ charge$
$B': shape\ factor$

On the other hand, in UV irradiation, a nanosecond pulsed laser is used, and a large number of electron-hole pairs are generated along the trajectory of the UV light immediately after UV irradiation, and the hole density then decreases by diffusion and recombination, meaning that the hole density is a function of space and time, $\Delta p_{UV}(x,t)$. At time zero (immediately after the irradiation), the depth profile of hole density is determined by the number of photons injected by UV light and the optical properties of the irradiated object, such as reflectivity and absorption coefficient, as in Eq. 2. As a general solution, the hole density generated by a single pulse is expressed as Eq. 3 by solving the diffusion equation [4, 5] and it appears repeatedly according to the frequency of the UV pulse.

$$\Delta p_{UV}(x,0) = g_0 \exp(-\alpha x). \tag{2}$$

$where\ \alpha\ is\ an\ absorption\ coefficient\ of\ excitation\ source\ (laser\ light)\ and$
$g_0 = N_0\alpha\,(1-R)/(1-Re^{-\alpha W})$
$N_0: number\ of\ photons\ per\ unit\ area\ emitted\ from\ laser$
$R: reflectivity$
$W: drift\ layer\ thickness$

$$\Delta p_{UV}(x,t) = \sum_{n=1}^{\infty} \Gamma_n \Phi_n(x) F_n(t). \qquad (3)$$

$where\ \Phi_n(x)\ are\ spatial\ functions\ with\ parameters\ of\ drift\ layer\ width,\ surface/interface\ recombination\ velocities\ and\ ambipolar\ diffusion\ coefficient.$

$F_n(t)\ are\ time\ dependent\ terms\ with\ parameters\ of\ ambipolar\ diffusion\ coefficient\ and\ lifetime\ in\ drift\ layer.$

$\Gamma_n\ are\ constants\ including\ initial\ hole\ density\ g_0\ at\ x = 0, t = 0\ and\ absorption\ coefficient\ \alpha\ of\ excitation\ source\ (laser\ light).$

Therefore, the UV irradiance should be set so that the peak value of hole density induced by UV irradiation (t=0) is equal to the hole density at the i/n+ interface during forward biased.

$$\Delta p_{FB}(W) = \Delta p_{UV}(W, 0). \qquad (4)$$

The Eq. 4 was compared with the results of the correlation experiments performed by the authors on the PiN diodes fabricated on a 4" particular wafer [2]. The sample was a commercially available n-type 100 mm Φ 4H-SiC wafer with a 4° off-cut angle. The structure of the PiN diode was formed by doping aluminum (3×10^{18} cm^{-3}) on the Si face of the epi wafer (buffer layer (0.5 μm, 1×10^{18} cm^{-3}), drift layer (5.4 μm, 5×10^{15} cm^{-3})) with a nickel electrode on the entire backside of the wafer. An aluminum electrode array of comb pattern (2mm square chip) was formed in half of the wafer for accelerated current stress, and the other half has no electrode pattern for UV irradiation stress, as shown in Fig. 1. In the UV irradiation, the excitation source was 355 nm Nd: YAG-3HG (Yttrium Aluminum Garnet-third Harmonic Generation) pulsed laser with 10 ns pulse width per 20 μs cycle (duty 0.05%) with beam diameter of 3 mmΦ.

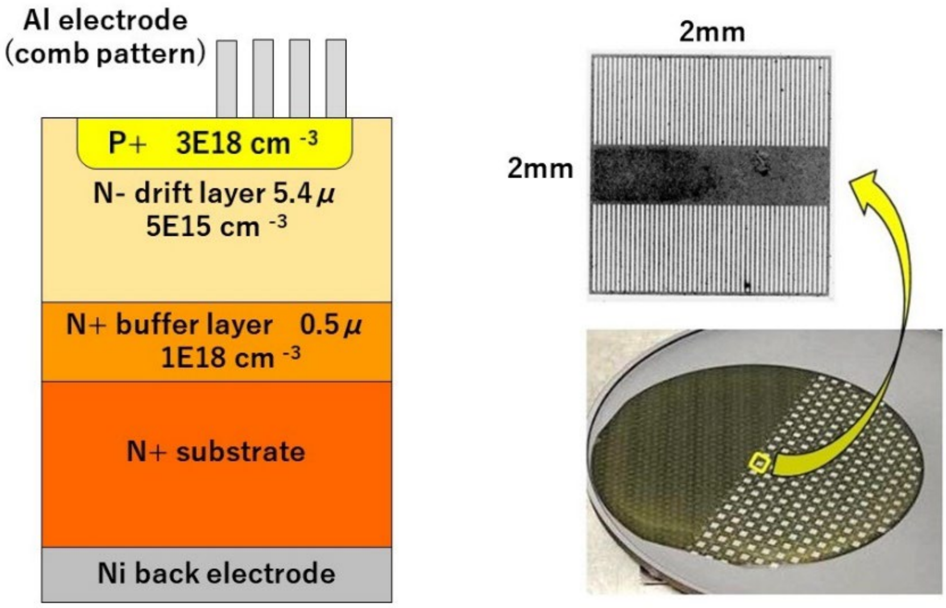

Fig.1. Schematic diagram of the PiN diode and photos of aluminum electrode pattern on SiC Epi wafer

In the experiment, the expansion velocity (glide velocity of the Si(g) core partial dislocation at the leading edge of the 1SSF in the $\langle 1\,\bar{1}\,0\,0\rangle$ direction) was measured for 329 bar shaped defects expanded by forward bias stress test with multiple levels of current density and for 11 bar shaped defects expanded by UV irradiation stress with multiple levels of irradiance. From the data obtained, the point at which the expansion velocity becomes zero was estimated by regression analysis, and that value was determined as the threshold value at which the expansion occurs, with the results that *235 A/cm²* and *36,650 W/cm²* were the estimated thresholds in forward bias and in UV irradiation, respectively. Then, the hole densities for both cases were calculated. Although Eq. 1 is an equation for a simple p/i/n+ structure for a PiN diode, the sample used in the experiment has a p/i/n+/n++ structure with a buffer layer as shown in Fig. 1, and Eq. 1 cannot be used to accurately calculate the hole density. Therefore, a one-dimensional device simulator, AFORS-HET was used in forward bias case, and in UV irradiation case, Eq. 2 was used. The calculated hole densities were:

$$\Delta p_{FB}(W) = 7.644 \times 10^{16}\ cm^{-3}$$
$$\Delta p_{UV}(W,0) = 1.174 \times 10^{17}\ cm^{-3}$$

This means the relationship of

$$\Delta p_{FB}(W) = \beta \cdot \Delta p_{UV}(W,0) \quad ,\beta \approx 0.65. \tag{5}$$

It differs from Eq. 4 and there are two possible reasons why $\beta \neq 1$.

(i) It is just an experimental error and $\beta \sim 1$.

(ii) The peak of hole density induced by UV pulse irradiation certainly matches the hole density in forward bias case, but the hole density rapidly decays after the pulse irradiated. If the density must remain above the threshold for a certain period of time in order for the Si(g) core to glide, the peak of the hole density by UV irradiation must be somewhat above the threshold. Therefore, a correction term β (<1) is needed in Eq. 5.

Since this can only be determined by future research and experimental validation, Eq. 5 with the condition of $\beta \leq 1$ is employed at this point, instead of Eq. 4 to express the correlation. From the above, for a given current density, the irradiance E_{UV} can be set by replacing the right side of Eq. 5 with the irradiation conditions,

$$E_{UV} = \frac{1}{\beta} \cdot e_0 \cdot f \cdot \frac{1 - Re^{-\alpha W}}{\alpha(1-R)e^{-\alpha W}} \cdot \Delta p_{FB}(W). \tag{6}$$

$$where\ e_0 : 5.596 \times 10^{-19}\,J\ = one\ photon\ energy\ \ at\ 355nm$$
$$f\ :\ laser\ pulse\ requency$$

The results are shown in Fig. 2. The solid line shows the case where the peak hole density by UV radiation coincides with the hole density by forward bias (β=1), and the dashed line shows the case where the experimental value ($\beta \approx 0.65$) is reflected in Eq. 5. Thus, the irradiance can be set according to the forward bias condition.

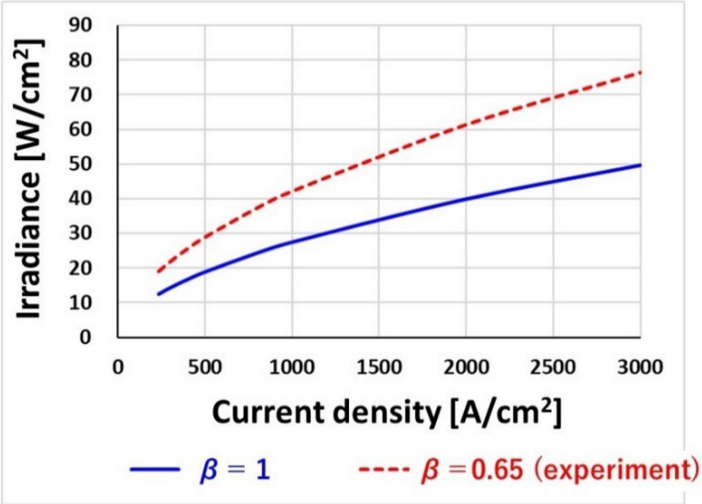

Fig.2. Irradiance-current density equivalence curve

Irradiation Time Determination (Equivalent Time Corresponding to Forward Bias)

The irradiation time of UV pulsed laser is thought to be shortened by increasing the pulse width and/or increasing the frequency to elicit the same effect of defect expansion, but the pulse width and frequency are optimized in the laser system to obtain stable output and cannot be much changed. This means that UV irradiation time cannot be significantly reduced while maintaining the same peak hole density. Therefore, here is calculated that how long the UV irradiation time would be if it is converted in case of forward bias. In other words, calculate what the ratio of the time (forward biasing time to irradiation time) to reach an equivalent defect expansion (the same length of 1SSF expansion) would be if the current density and UV irradiance are set to meet Eq. 5 in the previous section.

Since the hole density is in a steady state under a constant current flow at forward bias, 1SSF always expands as long as the current density exceeds a certain threshold. In the case of UV irradiation, on the other hand, the hole density decays to a level below the threshold right after the UV pulse irradiation, so 1SSF expands only during it exceeds the threshold. Therefore, the total amount of expansion during in forward bias or in UV irradiation is expressed by (hole density above the threshold) × (period during which the density is above the threshold), i.e. the integral of the hole density exceeding the threshold over time, as shown in Fig. 3 (the shaded area in UV irradiation case). Accordingly, the total amount of expansion in unit time by forward bias and that in unit time by UV irradiation are independently calculated and can be connected via equal amount of expansion as follows.

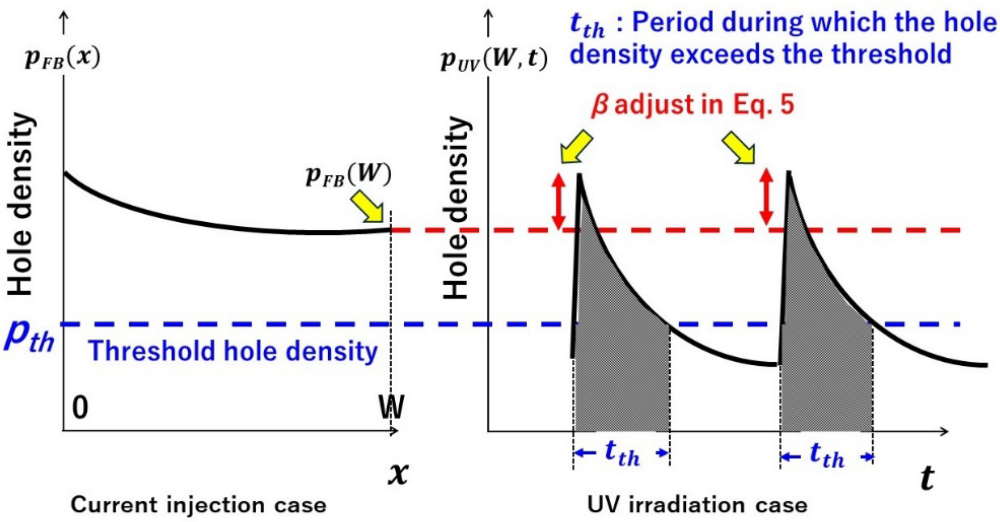

Fig.3. Duration of 1SSF expansion (shaded area)

$$\Delta p_{FB}(W) = r_{eq} \cdot \left(\int_0^{t_{th}} \Delta p_{UV}(W,t)dt \right) \cdot f. \tag{7}$$

$$\textit{where } r_{eq}\text{: UV irradiation time multiplier}$$

$$t_{th}\text{: period during which the hole density exceeds the threshold}$$

Clearly, the term $r_{eq.}$, which is referred to as UV irradiation time multiplier, is more than unity. This means that to create a condition equivalent to forward bias by UV irradiation, the UV irradiation time can be set to $r_{eq.}$ times the forward bias time.
From equations (2), (3) and (7),

$$r_{eq} = g_0 e^{-\alpha W} \Big/ \left\{ f \cdot \left(\int_0^{t_{th}} \sum_{n=1}^{\infty} \Gamma_n \Phi_n(W) F_n(t) dt \right) \right\}$$

$$= g_0 e^{-\alpha W} \Big/ \left\{ f \cdot \sum_{n=1}^{\infty} \Gamma_n \Phi_n(W) \left(\frac{1 - e^{-\gamma_n t_{th}}}{\gamma_n} \right) \right\} \tag{8}$$

$$\textit{where } \gamma_n \equiv \frac{1}{\tau_i} + a_n{}^2 D_a$$

a_n: *the solutions of characteristic equation with the surface/interface recombination velocity, the ambipolar diffusion coefficient and the drift layer thickness as parameters.*

D_a: *ambipolar diffusion coefficient*

After the UV pulse is applied, the decay curve of the hole density depends on carrier lifetime and surface recombination velocity of the specimen, which affects the UV irradiation time multiplier $r_{eq.}$ in Eq.8. The variation of $r_{eq.}$ when the surface recombination velocity of the specimen is varied from 1,000 cm/s to 50,000 cm/s is shown in Fig. 4, which indicates that even though the surface recombination velocity is not precisely known, the same amount of expansion can be achieved between forward bias and UV irradiation if the UV irradiation time is set one or two digits longer than forward bias time.

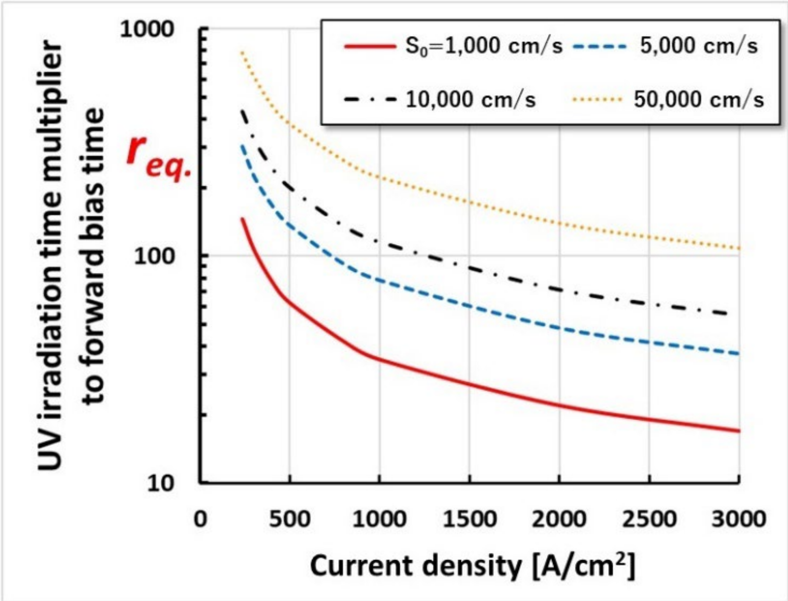

Fig.4. UV irradiation time multiplier: ratio of time required for UV irradiation to time required for forward bias

Summary

In this article were described the setting values of UV irradiation conditions (irradiance and irradiation time) corresponding to forward bias conditions to simulate the bipolar degradation. As for the irradiance, it was so determined that the hole density at the i/n+ interface is equal to that in forward bias case, but regarding the irradiation time, it was found that one to two digits more time is required to expand 1SSF by the same amount as in forward bias case. Although UV irradiation may seem to be less efficient for defect expansion than forward bias, for the defect screening purpose, it is sufficient if the defects expand to the point where they can be identified as defects. Since the expansion rate (glide velocity of Si(g) core) at several hundred A/cm^2 is reported to be about several hundred microns per minute [2], even if converted to UV irradiation case, it is within the time range that can be adoptable as a screening process and UV irradiation can be effectively used for screening.

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