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Sub-bandgap light-induced carrier generation at room temperature in Silicon Carbide MOS capacitors

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Abstract. Carrier generation characteristics in n-type substrate SiC MOS capacitors induced by sub-bandgap energy light are reported. The generation rate is high enough to create an inversion layer in ~20 minutes with monochromatic light (front side illumination) of energy 2.1 eV in 4H-SiC for electric fields smaller than 1 MV/cm. Generation and recovery results strongly indicate involvement of a metastable defect whose efficiency as a generation center increases under hole-rich and decreases under electron-rich conditions. The generation dependence on bias history and light energy shows the defect to have properties consistent with the metastable silicon vacancy / carbon vacancy-antisite complex (V_{Si} / V_c - C_{Si}).

Sub Bandgap Optical Generation and Annealing. Silicon carbide (SiC) has traditionally suffered from a large number of defect levels in the energy gap[1] and very high SiC/SiO_2 interface trap densities[2]. Several defect characterization experiments have reported generation lifetimes much smaller than for Silicon at both the SiC/SiO_2 interface[3] and in the SiC substrate[4]. In this study, we report generation characteristics in n-type substrate SiC MOS capacitors induced by sub-bandgap energy light. The generation rate is high enough to create an inversion layer in ~20 minutes due to front-side illumination (where only the edges of the device are exposed to the incident light) with monochromatic light of energy 2.1 eV in 4H-SiC (E_g = 3.2 eV) for -5V bias on a capacitor with 70 nm oxide thickness. It is surprising that such high generation rates can be achieved at room temperature (where $n_i = 10^{-8}$ cm^{-3} for 4H-SiC and the thermal generation rate is negligible) with light having energy much lower than the bandgap.

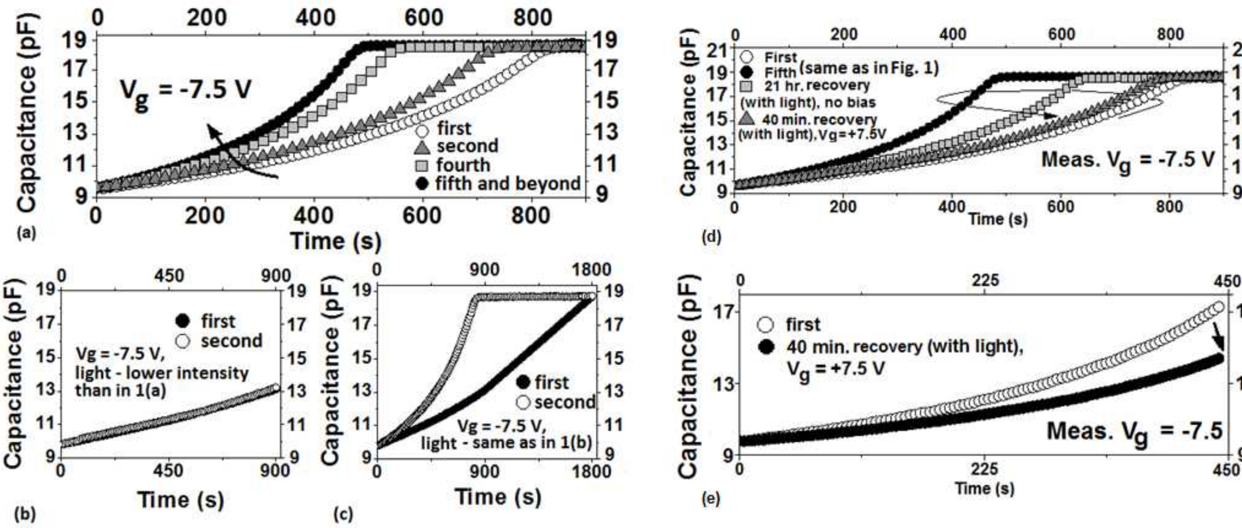

Fig.1 (a). C-t sweeps at 1 kHz (V_g = -7.5 V) under broad spectrum (predominantly yellow) light at room temperature. (b) C-t sweep on a second device - performed for the same time and bias using much lower intensity light. (c) C-t sweep on the same device (Fig. 1b) using the same low intensity light (as Fig 1b). (d). Room temperature recovery characteristics of the device shown in Fig.1a after recovery at zero bias (21 hrs.) and at accumulation bias (V_g = +7.5 V) for 40 mins., first with and then without light. (e) C-t sweeps for a fresh device and then after a 40 min bias under light at V_g = +7.5 V.

Generation appears to be dominated by a two-photon process on a defect exhibiting metastability whose efficiency as a generation center increases under hole-rich and decreases under electron-rich conditions.

N-type 4H-SiC MOS capacitors from the wafer line monitor of a state-of-the-art SiC MOSFET manufacturer were used in this study. Similar experiments on 6H-MOS capacitors from a slightly older process showed the same trends. The pulsed capacitor method, which is a conventional technique to study generation lifetime characteristics in MOS systems, was used[5]. Fig. 1a shows C-t measurements at 1 kHz on a device biased in deep depletion at -7.5 V. The sweeps were performed at room temperature. The probe station microscope lamp (a predominantly yellow light source) was used for illumination. Although the ambient daylight was much more efficient at generation, the microscope light in a closed cabinet was used to ensure constant intensity.

Capacitance values show almost no change over a range of 1 kHz to 1 MHz. The rate of increase of capacitance with time (dC/dt) increases with every sweep and finally reaches saturation. However, when the sweep is performed for the same time and bias using a much lower intensity light (Fig. 1b), subsequent C-t sweeps show negligible increase in dC/dt. Using the same low intensity light (as in Fig 1b) when the same device is swept for a longer period of time (so that the capacitance reaches values close to the inversion capacitance) subsequent C-t sweeps show a prominent increase in dC/dt. Thus, the increase in dC/dt in subsequent sweeps is related not to the bias, time, or intensity of light – but to the value of capacitance reached in the previous sweep.

The most important thing to note in Fig. 1 is that every sweep starts from the same capacitance value. This rules out the increase in dC/dt to be due to any trapping or detrapping of bulk oxide charge. While the capacitance is rising, eliminating the light while maintaining the bias causes almost no decay in the capacitance. This clearly shows that the rise in capacitance is not related to the detrapping of only electrons from deep levels. In the absence of optical excitation, traps that have emitted electrons should be quickly filled in an n-type material, since they are empty following emission and free electrons are available to fill up the empty states. Detrapping only holes from deep levels also cannot account for the rise in capacitance because trapped holes should not be stable in an n-type material. Generation of electron-hole pairs does not result in a change in occupancy of a trap, and the absence of empty traps makes it difficult for generated carriers to be captured. So, when the light is withdrawn, a reduction in the number of free electrons and holes can result only from recombination, which is very slow in the presence of a bias strongly separating electrons from holes. Thus, the absence of any significant decay in capacitance following the withdrawal of optical excitation clearly shows that the rise in capacitance is due to the generation of electron hole-pairs.

Figs. 1d and 1e show the recovery characteristics of the device. During recovery, the light was kept at the same level as during stress or measurement to eliminate any bias-independent effects. The device steadily recovered to a lower generation rate (Fig. 1d) in about 21 hours. However, the generation rate was still higher than the pre-stress generation rate. There was a significant increase in recovery when the device was biased in accumulation. Fig. 1d also shows the recovery of the same device at accumulation bias (V_g = +7.5 V) for 40 min with the same intensity light. The accumulation bias was started right after recording the 21 hour recovery in Fig. 2. Fig. 1e shows the C-t sweeps for another device – first for the fresh device and then after a 40 min bias under light at V_g = +7.5 V. After bias at accumulation, the generation rate is lower than that in the fresh device. Thus, the generation rate increase can be "super recovered".Fig. 2. shows the zero bias recovery characteristics of the device in greater detail. During recovery – the light is kept at the same level as during stress or measurement. The time intervals between successive sweeps from the first to the third recovery measurement were 8, 20 and 60 min, during which the device steadily recovered to lower generation rates (direction shown by large arrow in Fig. 2 - left). The next sweep was performed after 2 hours and this showed a slight increase in the generation rate. The increase continued and reached saturation in about 18 hours (small arrow in Fig. 2 - left). The capacitance rate increase under zero bias shows that not only does the hole rich condition of the MOS capacitor enhance the generation rate – but even at zero bias, the illumination causes a slow increase in generation lifetime – the cumulative effect of which over several hours can be significant. The device recovery is stronger when the accumulation type bias is applied under light than without it (Fig. 2 – right).

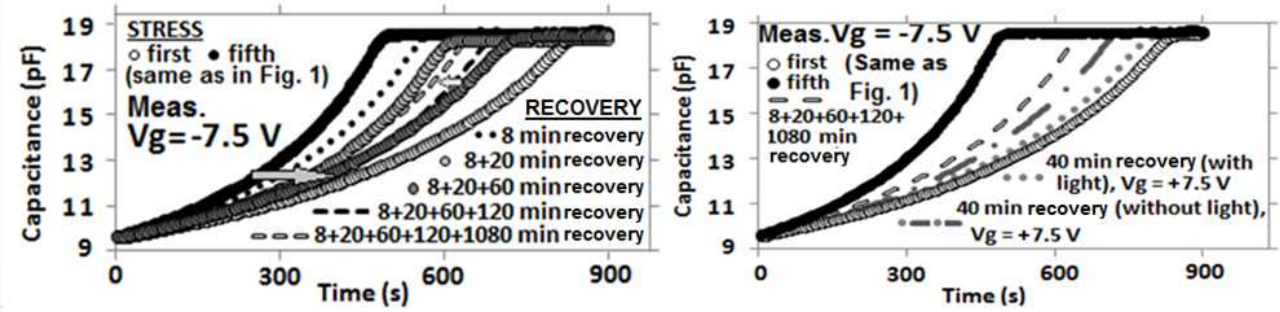

Fig. 2 (left). Zero bias recovery characteristics (large arrow) under illumination for device shown in Fig.1. After first three sweeps showing recovery – the capacitance rise rate increases slightly (small arrow) and reaches saturation. (right) Recovery of the same device at accumulation bias (V_g = +7.5 V) for 40 mins. first with and then without the light.

The results are very similar to previously reported thermal generation characteristics [3] where generation rate was proposed to be dominated by interface states. However, Fig. 3 (left) shows an increase in the steady-state reverse bias current of an n-substrate Schottky diode under the same sub-bandgap energy microscope lamp illumination by at least three orders of magnitude, strongly indicating that sub-bandgap generation is related to a bulk SiC defect and not the SiC/SiO_2 interface. The bias history dependence and super recoverable nature of the generation rate strongly indicates that the defect is metastable – switching configurations under electron-rich and hole-rich conditions.

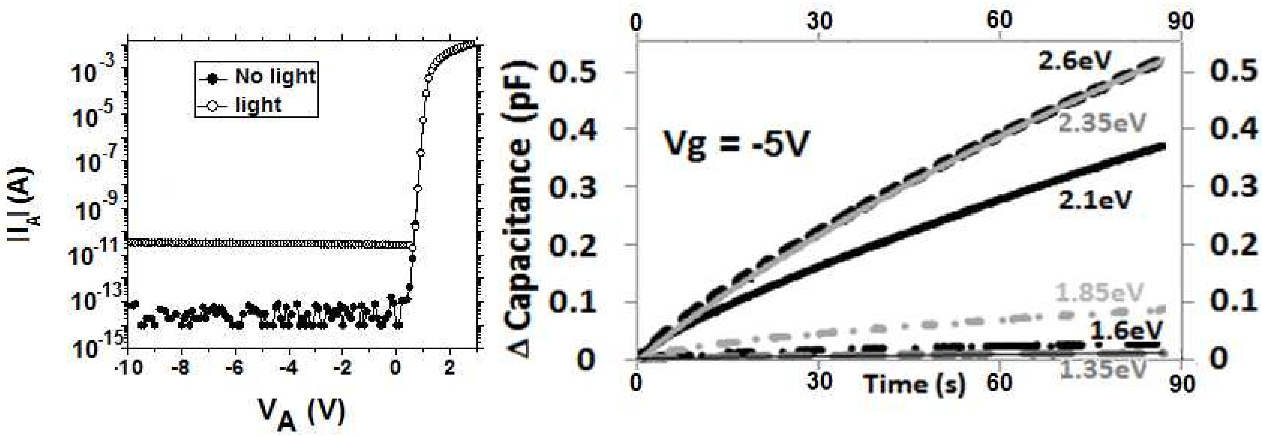

Fig. 3.(left) 4H-SiC Shottky diode characteristics with and without the microscope lamp. (right) C-t sweeps using monochromatic light for energies ranging from 1.35 to 2.6 eV. Small sweep times chosen so as to not raise capacitance enough to affect the generation rate for next sweep.

Energy Dependence under Illumination with Monochromatic Light. To study the generation rate as a function of light energy, C-t sweeps were performed using monochromatic light consisting of energies ranging from 0.6 to 3.5 eV. Light from a broadband Xe source was dispersed using a ¼ m monochromator with appropriate mode-sorting filters to achieve 0.05 eV resolution at a photon flux of $\sim 5 \times 10^{16}$ $cm^{-2}s^{-1}$. Short sweep times were chosen so as to not raise the capacitance enough to affect the generation rate for the next sweep. The generation rate shows the first significant increase (on the order of what is observed with the microscope lamp) above 1.6 eV (Fig. 3 - right). The maximum increase is observed between 1.85 and 2.1 eV. After 2.35 eV, the generation rate does not increase further for higher energies up to 3.2 eV (sub-band energies above 2.6 eV not shown in for clarity) where band-to-band generation takes over.

Generation rates becoming comparable to the microscope lamp-induced rates above 1.6 eV clearly indicates that the process is dominated by transitions involving two photons. Thus, for different defects, the one with a level closest to midgap will require two photons of minimum energy to generate. The generation characteristics show close similarities to the silicon vacancy (V_{Si}) which has been shown to be metastable [6,7]– transforming to a carbon vacancy-antisite complex V_c - C_{Si} for Fermi level positions at and below midgap. While V_{Si} in 4H-SiC has the closest level (charge state transition from -1 to -2) to midgap at E_v + 2.01eV, V_c - C_{Si} has the closest level (charge state transition from +1 to 0) to midgap at E_v + 1.39 eV [8]. Thus, a configuration change of V_{Si} to V_c - C_{Si} under hole-rich conditions would result in the minimum energy of each of the 2 photons required for a generation event to be reduced from 2.01 eV to 3.2 – 1.39 = 1.81 eV.

Charge State →	**(+2/+1)**	**(+1/0)**	**(0/-1)**	**(-1/-2)**	**(-2/-3)**	**(-3/-4)**
V_{Si}			0.56	**2.01**	2.05	2.81
V_c - C_{Si}	0.83	**1.39**	2.11	2.56	3.12	

TABLE I. Defect levels (energy from E_v) for V_{Si} and its metastable version V_c - C_{Si} as calculated in 4H-SiC at the hexagonal site through density functional theory [8]. Levels closest to midgap are highlighted in boldfont.

The saturation of the generation rate around photon energies of 2.35 eV for sub-bandgap energies is likely due to the fact that some of the shallowest levels have electron capture times for levels close to the valence band and hole capture times for levels close to the conduction band too low to generate through a two photon process. V_c - C_{Si} has a level (+2/+1) closest to the valence band at ~0.83eV [8], showing very close consistency with the experimental result of the generation rate saturating at 3.2 – 0.83 ≈ 2.35 eV.

Conclusion. We have demonstrated unexpectedly high generation rates in state-of-the-art SiC MOS capacitors at room temperature for electric fields less than 1 MV/cm due to illumination with light more than 1eV smaller in energy than the SiC bandgap. Generation and recovery results strongly indicate the involvement of a defect exhibiting metastability, whose efficiency as a generation center increases under hole-rich and decreases under electron-rich conditions. The generation rate dependence on bias history and monochromatic light energy shows the defect to have properties consistent with the metastable silicon vacancy (V_{Si}) / carbon vacancy-antisite complex (V_c - C_{Si}).

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