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Sub-Bandgap Light-Induced Carrier Generation at Room Temperature in Silicon Carbide MOS Capacitors

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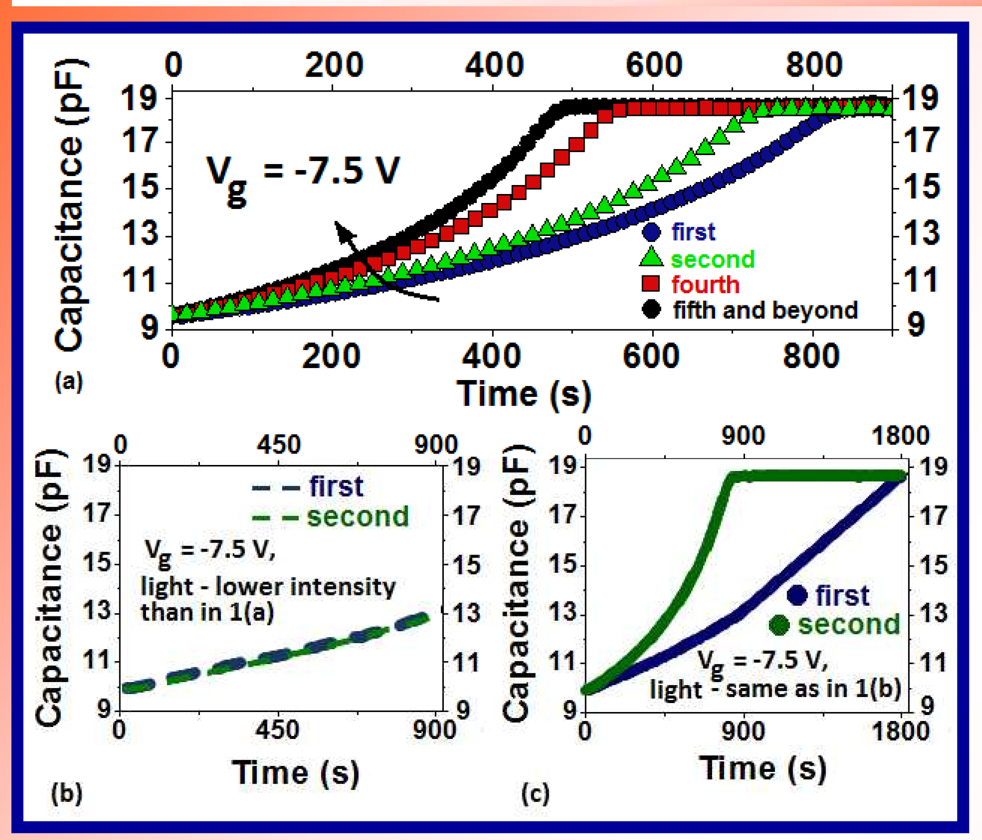
ABSTRACT

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. 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}).

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 1 eV 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}).

PULSED MOS CAPACITOR WITH MICROSCOPE LAMP

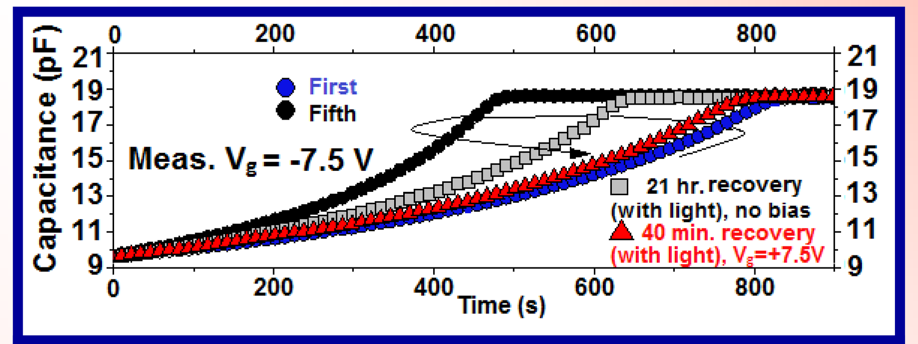


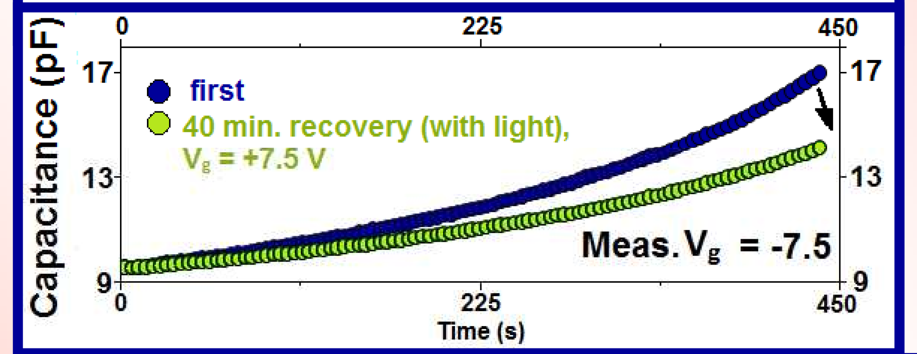
- ❑N-type 4H-SiC (E_g = 3.2 eV) capacitors from the wafer line monitor of a state-of-the-art SiC MOSFET manufacturer used.
- ❑Oxide thickness = 70 nm.
- ❑Microscope lamp (halogen - 15 W) was used at < 10 % of maximum intensity.
- ❑V_g = -7.5 V, frequency = 1 kHz (Capacitance values show no change over a range of 1 kHz to 1 MHz).
- ❑6H-SiC (from older process) shows similar results.

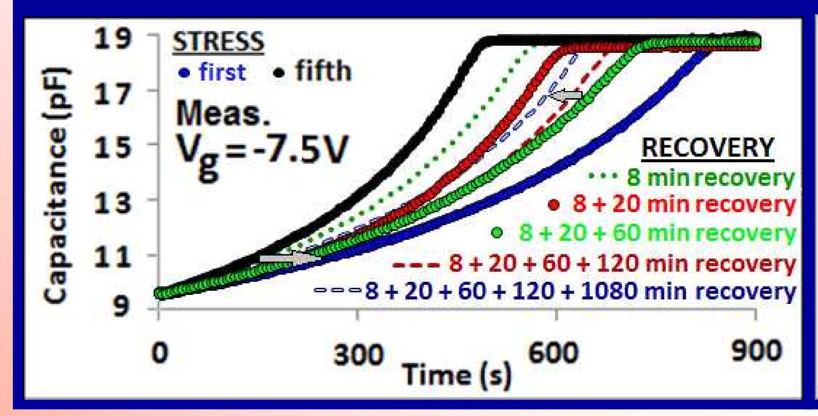
KEY OBSERVATIONS

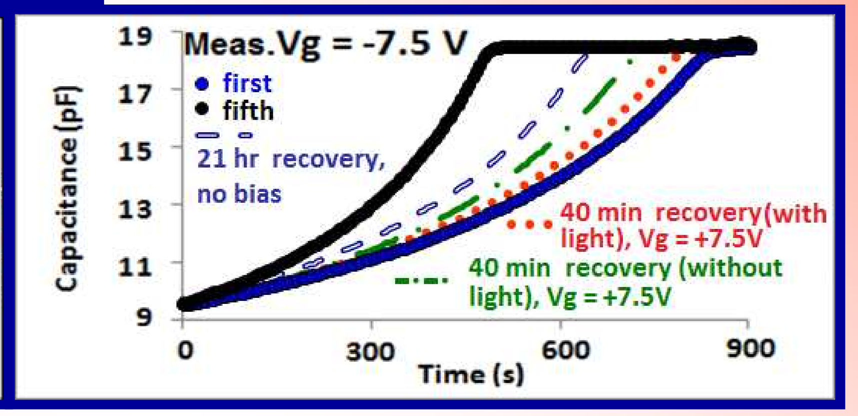
- ❑**The rate of increase of capacitance with time (dC/dt) increases with every sweep and finally reaches saturation**
- ❑When the sweep is performed for the same time and bias using much lower intensity light (Fig. 1b), subsequent C-t sweeps show negligible increase in dC/dt. Using the same low intensity 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 prominent increase in dC/dt.
- ❑**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**
- ❑**Increase in dC/dt not due to any trapping or detrapping of bulk oxide charge (every sweep starts from the same capacitance value)**
- ❑While the capacitance is rising, eliminating light while maintaining bias causes almost no decay in the capacitance
- ❑**Rise in capacitance not due to detrapping one carrier type from deep traps – true generation**
- ❑At maximum lamp intensity – inversion can be reached in less than 5 seconds

RECOVERY OF GENERATION CHARACTERISTICS





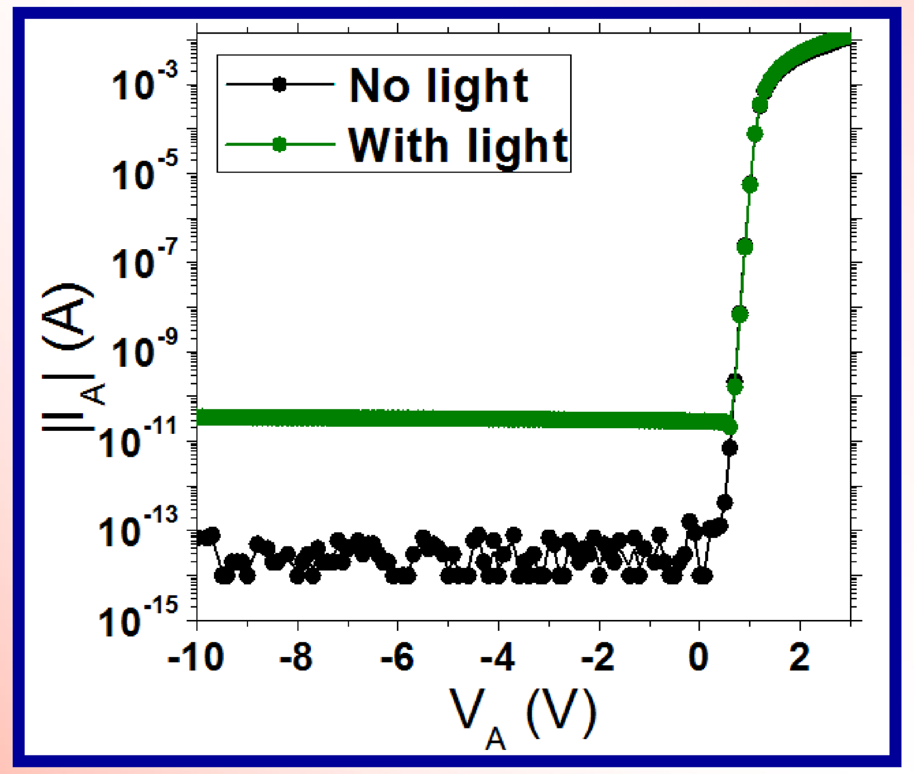




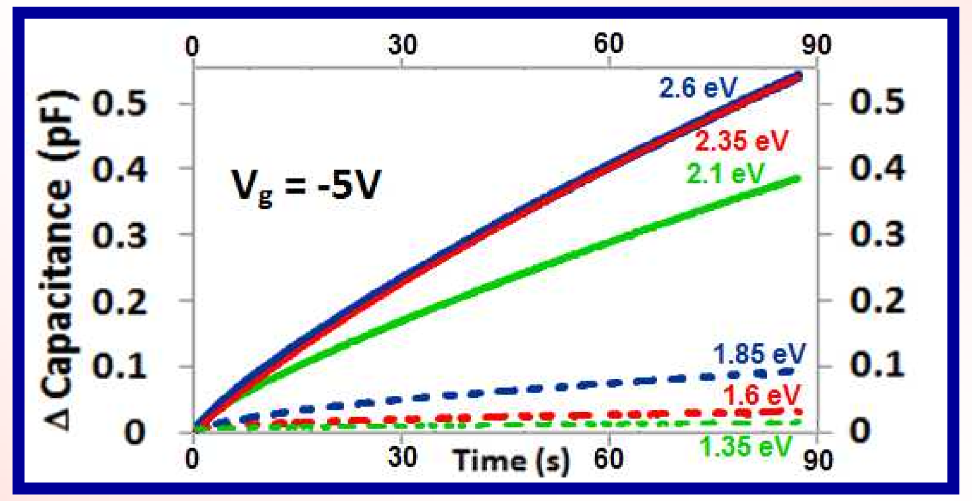
- ❑Light kept at the same level during recovery as during stress or measurement
- ❑Device steadily recovered to a lower generation rate in about 21 hours
- ❑**Significant increase in recovery when the device was biased in accumulation**
- ❑**Degradation can be super-recovered (unlike a process involving the removal and diffusion of hydrogen)**
- ❑Some increase in generation rate evident due to light exposure, even with no bias
- ❑Recovery at accumulation bias stronger under light than under no light

SURFACE OR BULK GENERATION ?

- ❑Sub-bandgap generation could be happening in SiC bulk or at SiC/SiO_2 interface
- ❑ N-substrate Schottky diodes were illuminated with same sub-bandgap energy microscope lamp light
- ❑ At least 3 orders of magnitude increase in steady state diode reverse current
- ❑**Strong indication of sub-bandgap generation from a bulk defect.**



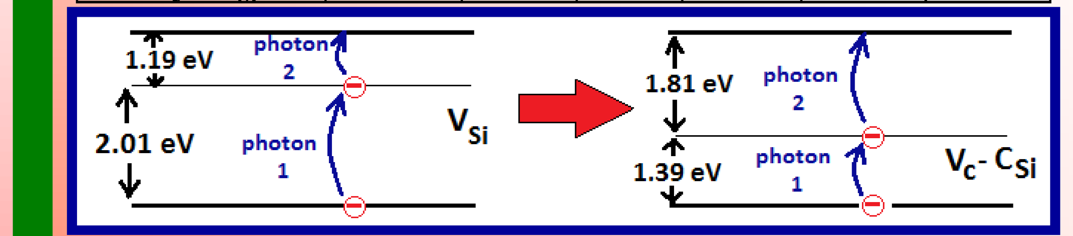
GENERATION WITH MONOCHROMATIC LIGHT



- ❑C-t sweeps performed using monochromatic light (0.6 to 3.5 eV).
- ❑0.05 eV resolution at a photon flux of ~5×10^{16} $cm^{-2}s^{-1}$.
- ❑Short sweep times chosen to not raise the capacitance enough to affect generation rate for next sweep.
- ❑Generation rate shows first significant increase (on the order of what is observed with the microscope lamp) above 1.6 eV.
- ❑**Strong indication of generation happening through 2 photons.**
- ❑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-bandgap energies above 2.6 eV not shown in for clarity) where band-to-band generation takes over.

GENERATION THROUGH TWO PHOTONS AND THE METASTABLE SILICON VACANCY

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	

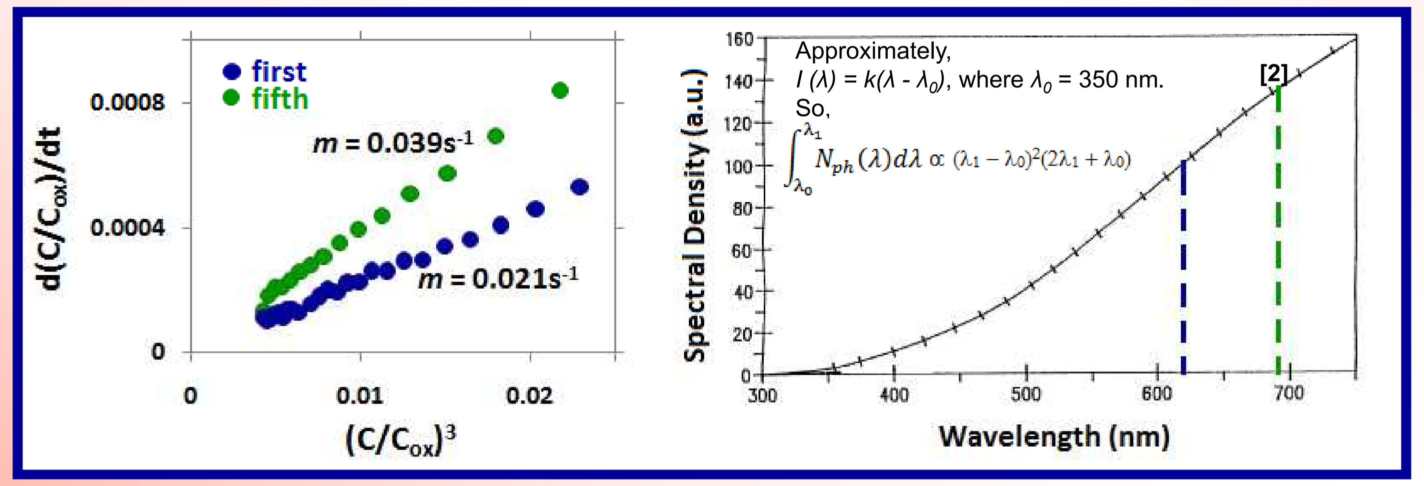


- ❑**Intensity of light is too low under all conditions for 2 photons to be absorbed by the same defect simultaneously (vanishingly improbable).**
- ❑**If generation is due to absorption of 2 photons within a time interval, the carrier capture in the intermediate state has to be stabilized by a structural deformation.**
- ❑Silicon vacancy (V_{Si}) has been shown to be metastable – transforming to a carbon vacancy-antisite complex (V_c - C_{Si}) for E_F at and below midgap
- ❑V_{Si} in 4H-SiC has the closest level (-1/-2) to midgap at E_v + 2.01 eV, V_c - C_{Si} has the closest level (+1/0) to midgap at E_v + 1.39 eV.
- ❑**V_{Si} → 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.**

CALCULATIONS CORRELATING METASTABLE V_{Si}/V_C - C_{Si} TO C-t BEHAVIOR

N_{ph} ∝ m, [1]
(N_{ph} = flux of photons with sufficient energy for generation),
$m = \Delta[d(C/C_{ox})/dt]/\Delta[(C/C_{ox})^3]$, [1]
m_{fifth}/m_{first} = 0.039/0.021 = 1.86 (experimental).

For a typical halogen lamp,
$N_{ph}(hv>1.8eV$ or $\lambda<690$ nm$)/N_{ph}(hv>2eV$ or $\lambda<620$ nm$)$ ~ 1.73



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[1] D.K. Schroder, IEEE TED 1972, [2] US Patent No. 5578892