Te-hyperdoped Silicon Carrier Dynamics

Qianao Yue, Ashikur Rahman, Renee Sher
Department of Physics, Quantitative Analysis Center, Wesleyan University, Middletown, CT 06459

WESLEYAN UNIVERSITY

Motivation

Silicon (Si) semiconductors have been used in a broad range of fields including photodetection devices and solar cells. Nevertheless, the photoresponsivity of intrinsic Si semiconductor has been limited by its **1.12-electron volt band gap**. One way of expanding the wavelength that intrinsic Si semiconductor can use is through doping. Adding dopants into the semiconductor introduces an **intermediate band** between valence band and conduction band. This facilitates electron excitation for low energy photons. However, such impurities inside the Si semiconductor also accelerate **carrier recombination**, a process, assisted by dopants, which electrons decay into valence band.

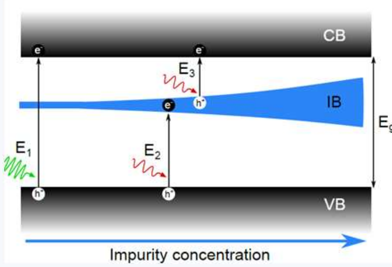


Fig. 1 Visualization of photoexcitation with the help of intermediate band (IB) with varying doping concentration (impurity). Adapted from Ref [1]

Experimental Set-up

We measured carrier lifetime using a non-contact method called time-resolved terahertz spectroscopy (TRTS). Terahertz waves (THz) are sensitive to free carriers in the material. By sending THz signal through Te-hyperdoped silicon before and after photon excitation, we can find the change in conductivity of the material. Optical pump was set to be a 400nm laser with pump power of 6mW and we varied pump power using ND filters.

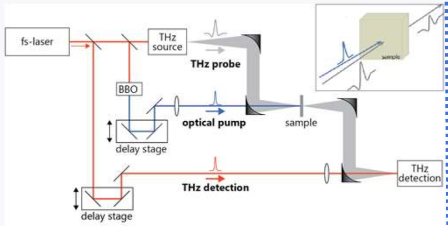


Fig. 2 Time-resolved terahertz spectroscopy (TRTS) set-up.

Te-hyperdoped silicon

Tellurium (Te) has been shown as a potential dopant for Si semiconductors. It has a low diffuse rate in Si substrate [2], allowing doping concentrations beyond material's solubility limit (called hyperdoping). Te-hyperdoped Si also shows thermal stability up to 400 Celsius [2]. Moreover, under decreasing temperature, Te-hyperdoped Si photodetectors show increasing spectral responsivity [2].

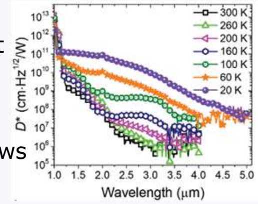


Fig. 3 Spectra Detectivity as a function of wavelength under zero bias at different temperatures from 20 to 300 K. Adapted from Ref [2]

In our experiments, we used Te-hyperdoped Si samples with peak concentrations of 0.25%, 0.5%, 1%, 1.5%, 2%, and 2.5%.

Research Question

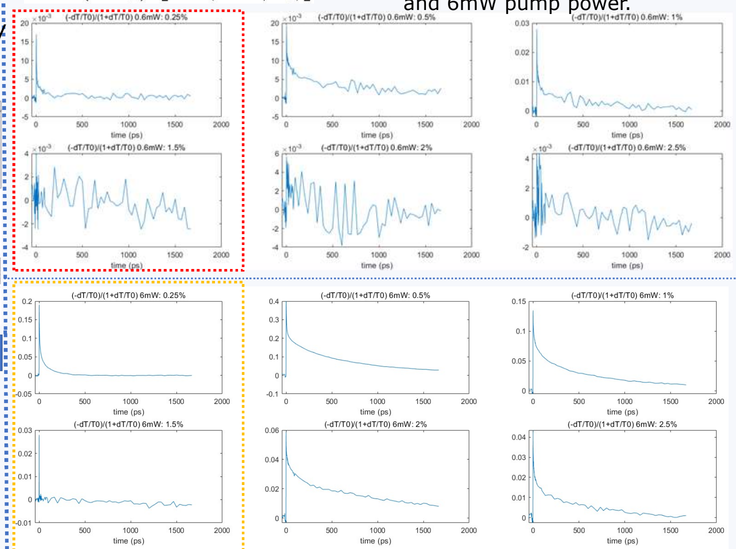
To understand why light detection properties depends on temperature, we want to study **how temperature variation influences carrier recombination and carrier lifetime.** This summer, the focus is on characterizing a set of samples and appropriate pump power for temperature dependent study.

Results

The time-dependent conductivities of the samples were calculated using the following relation [3]:

$$\sigma \propto \left(-\frac{\Delta T}{T_0}\right)\left[\frac{1}{1-(-\Delta T/T_0)}\right]$$

Fig. 4 (-ΔT/T0)/(1+ ΔT/T0) measured as a function of time for every concentration under 0.6 and 6mW pump power.



Results(continued)

From Fig. 4, we observed **significantly smaller carrier lifetime** for 0.25% and 1.5% sample in both 0.6 and 6mW pump power. For 0.6mW, the background noise was high for samples above 1.5% due to thermal excitation.

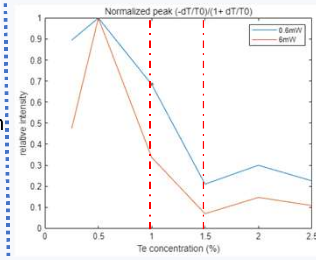
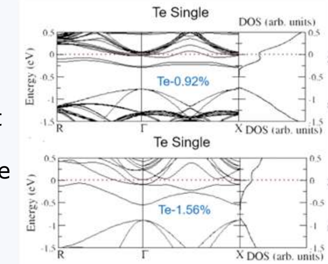


Fig. 5 Normalized peak intensity of (-ΔT/T0)/(1+ ΔT/T0) to 0.5% sample at each pump power

Fig. 6 Band structure and density of states for 0.92% and 1.56% Te-hyperdoped Si. Adapted from Ref [4]



From Fig 5, the normalized intensity showed a significant decrease between 1% to 1.5%. This corresponds to the **insulator to metal transition** (IMT) for Te-hyperdoped silicon.

Moreover, the two normalized curves in fig. 5 did not coincide with each other. This showed there is a nonlinear relation between pump power and peak conductivity. Hence, we performed a pump dependence measurement for 1% and 2% sample. We also fitted the curves with a bi-exponential decay model for quantitative comparison.

$$\left(-\frac{\Delta T}{T_0}\right)\Big/\left(\frac{1}{1-\left(-\frac{\Delta T}{T_0}\right)}\right) = \mathrm{a1} * \mathrm{Exp}\left[-\frac{t-t_0}{\tau_{\mathrm{long}}}\right] + (1-\mathrm{a1}) * \mathrm{Exp}\left[-\frac{t-t_0}{\tau_{\mathrm{short}}}\right]$$

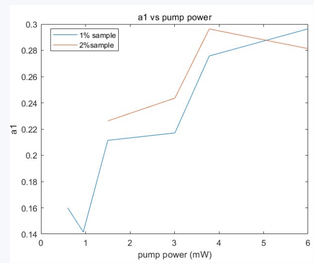


Fig. 7 showed an increase trend for constant a1 for 1% and 2% sample. It represents a longer carrier lifetime with increasing higher pump power. This can potentially be a **saturation effect** where too much electrons diffuse away from Te-dense region.

Fig. 7 Fitting constant a1 versus pump power for both 1% and 2%.

Future work:

- Perform temperature dependent measurement for 1% and 2% sample to observe samples above and below IMT.
- Use 1mW pump power prevent saturation effect and reduce background noise.
- Test samples' crystallinity to explain whether 1.5% and 0.25% sample behave differently due to crystal structure.

Work Cited

1. Lim, Shao Qi, and James S. Williams. 2022. "Electrical and Optical Doping of Silicon by Pulsed-Laser Melting" Micro 2, no. 1: 1-22. https://doi.org/10.3390/micro2010001
2. Wang, M., García-Hemme, E., Berencén, Y., Hübner, R., Xie, Y., Rebohle, L., Xu, C., Schneider, H., Helm, M., Zhou, S. 2021. "Silicon-Based Intermediate-Band Infrared Photodetector Realized by Te Hyperdoping " Adv. Optical Mater. https://doi.org/10.1002/adom.202001546
3. Hegmann, F.A., Ostroverkhova, O. and Cooke, D.G. 2005. "Probing Organic Semiconductors with Terahertz Pulses" In Photophysics of Molecular Materials, G. Lanzani (Ed.). https://doi.org/10.1002/3527607323.ch7
4. Mao Wang, A. Debernardi, Wenxu Zhang, Chi Xu, Ye Yuan, Yufang Xie, Y. Berencén, S. Prucnal, M. Helm, and Shengqiang Zhou. 2020. "Critical behavior of the insulator-to-metal transition in Te-hyperdoped S"Phys. Rev. B 102, 085204. https://doi.org/10.1103/PhysRevB.102.085204