Te-hyperdoped Silicon Carrier Dynamics

Qianao Yue, Ashikur Rahman, Renee Sher

Department of Physics, Quantitative Analysis Center, Wesleyan University, Middletown, CT 06459

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.

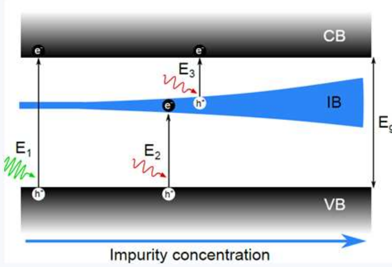


Fig. 1 Visualization of photoexcitation with the help of intermediate band (IB) with varying doping concentration (impurity). Adapted from Ref [1]

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.

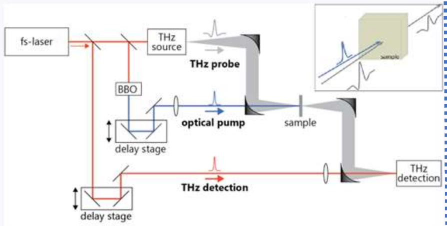


Fig. 2 Time-resolved terahertz spectroscopy (TRTS) set-up.

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

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].

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

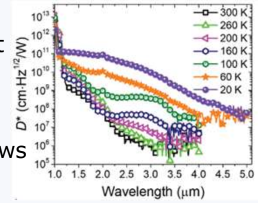


Fig. 3 Spectra Detectivity as a function of wavelength under zero bias at different temperatures from 20 to 300 K. Adapted from Ref [2]

Research Question

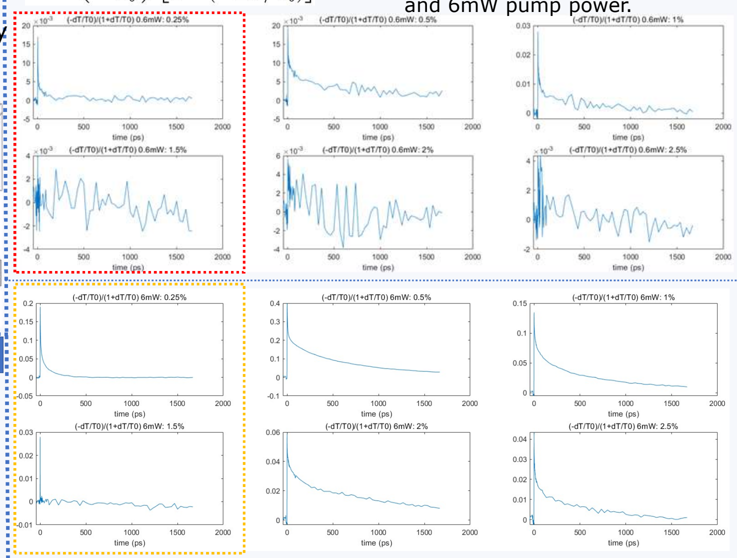
To understand why light detection properties depends on temperature, we want to study **how temperature variation influences carrier recombination and carrier lifetime.** This summer, the focus is on characterizing a set of samples and appropriate pump power for temperature dependent study.

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.

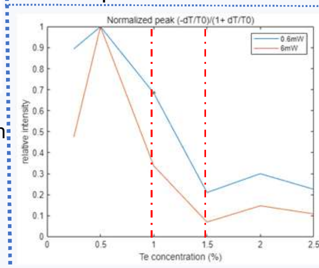
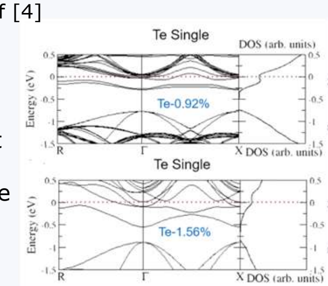


Fig. 5 Normalized peak intensity of (-ΔT/T0)/(1+ ΔT/T0) to 0.5% sample at each pump power

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.

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

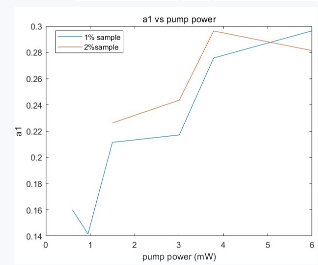


Fig. 7 showed an increase trend for constant a1 for 1% and 2% sample. It represents a longer carrier lifetime with increasing higher pump power. This can potentially be a **saturation effect** where too much electrons diffuse away from Te-dense region.

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.