Evaluating Effectiveness of Annealing Methods for Hyperdoped Silicon in Solar Cells

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Introduction

Hyperdoped silicon is an essential component in the production of solar cells. Pulsed laser melting and flash lamp annealing are two methods used to treat the silicon in the manufacturing process. Each method influences the distribution of dopant within silicon in different ways.

We are studying how a selected annealing process affects the light absorption and carrier lifetime properties in samples of titanium-hyperdoped silicon and gold-hyperdoped silicon.

Annealing Methods

Pulsed Laser Melting (PLM)

In this method of hyperdoping, ions of dopant (Au or Ti) are implanted into the silicon substrate. Melting of the silicon with a pulsed laser follows to repair the damage caused by ion implantation. The material is rapidly cooled and solidified to trap the dopant within the crystal.

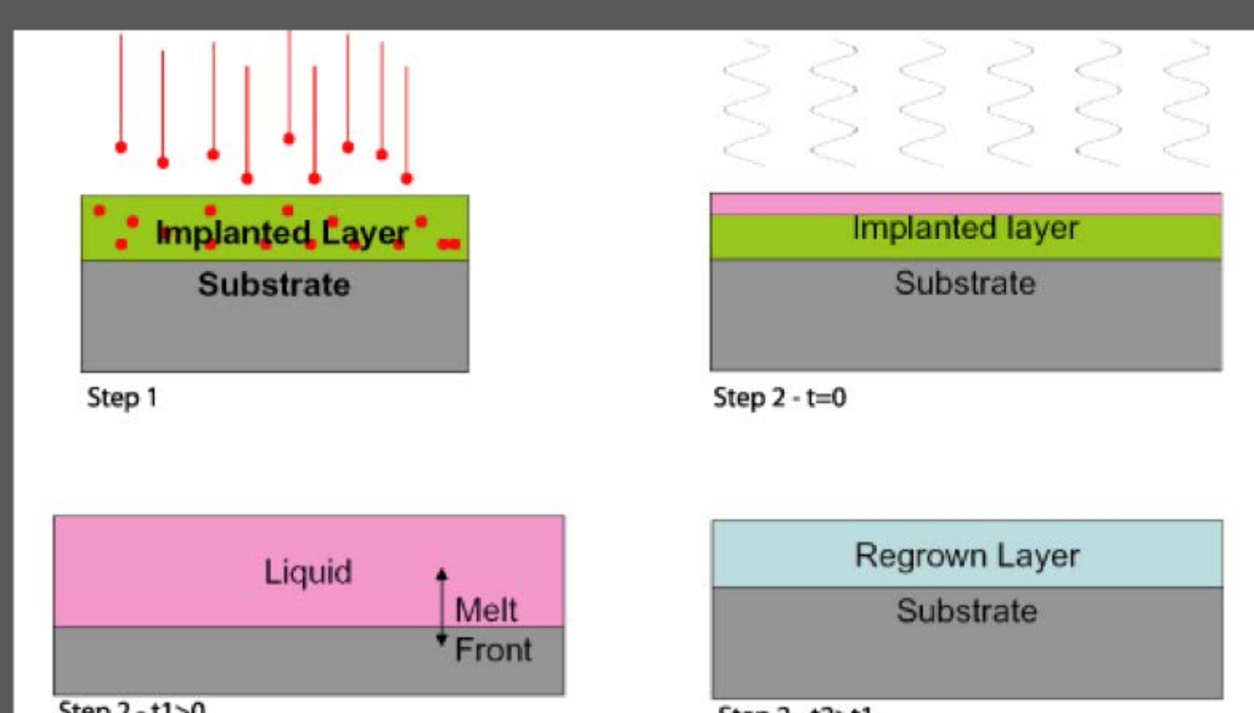


Figure adapted from M.A. Scarpulla, "Ion Implantation and Pulsed Laser Melting." *Solar Energy Materials Research Group*, Lawrence Berkeley National Laboratory

Flash Lamp Annealing (FLA)

Melting does not occur with this method. Instead, after ion implantation, the surface is heated with a flash lamp to near melting to repair damage (for Si, near 1687 K, or 1414 ℃).

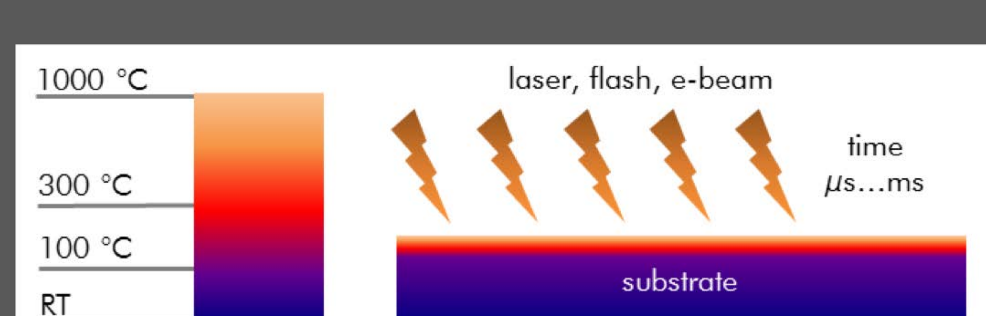


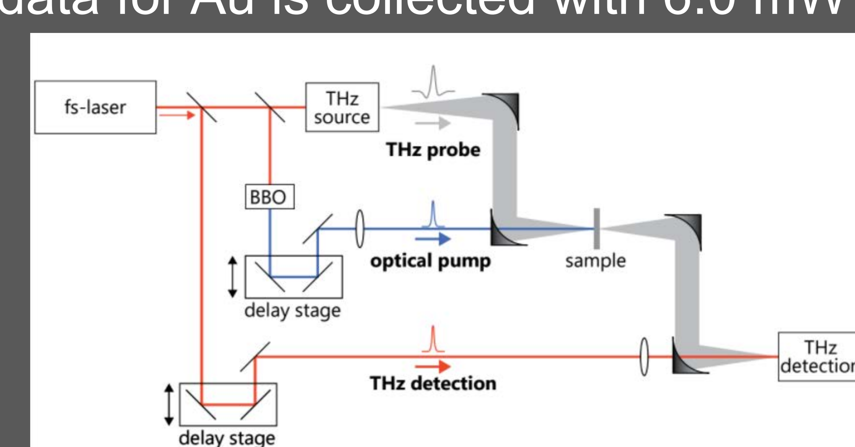
Figure adapted from M. Junghähnel and J. Westphalen, *Fraunhofer Institute for Organic Electronics*, Fraunhofer FEP – 2.0 – H03

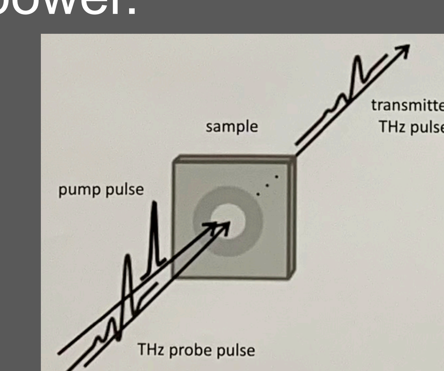
Experimentation

Charge carrier lifetimes are determined for six Ti-hyperdoped and six Au-hyperdoped silicon samples of different dopant concentrations. Ti implantation dose ranges from 2×10^{15} to $10\times10^{15}\ cm^{-2}$ and Au dose ranges from 0.7×10^{15} to $2.1\times10^{15}\ cm^{-2}$. At these doses, the resulting dopant concentration is near 1 atomic percent. Using time-resolved terahertz spectroscopy, a femtosecond laser beam is split into three:

- Optical pump pulse – to excite electron charge carriers
- THz probe pulse – to probe the conductivity or number of excited charge carriers
- THz detection – to detect THz probe pulses after it passes through the silicon sample

Sample conductivity is measured and plotted over time from the signal captured by the electrons excited. The resulting plots show a bi-exponential decay. From this, the carrier lifetime can be found. The standard pump pulse power is 0.6 mW. However, there is difficulty in detecting a signal for all Au FLA samples. Therefore, data for Au is collected with 6.0 mW laser power.





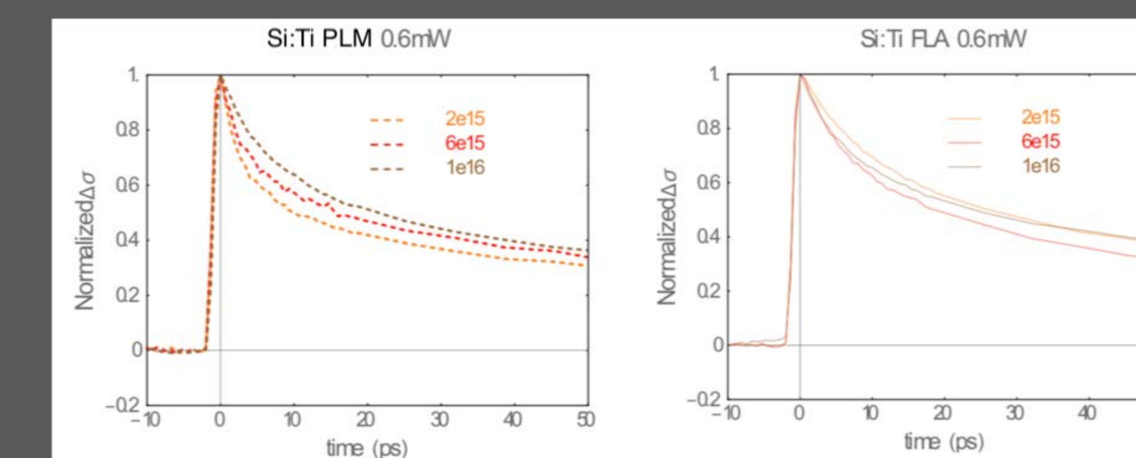
Results

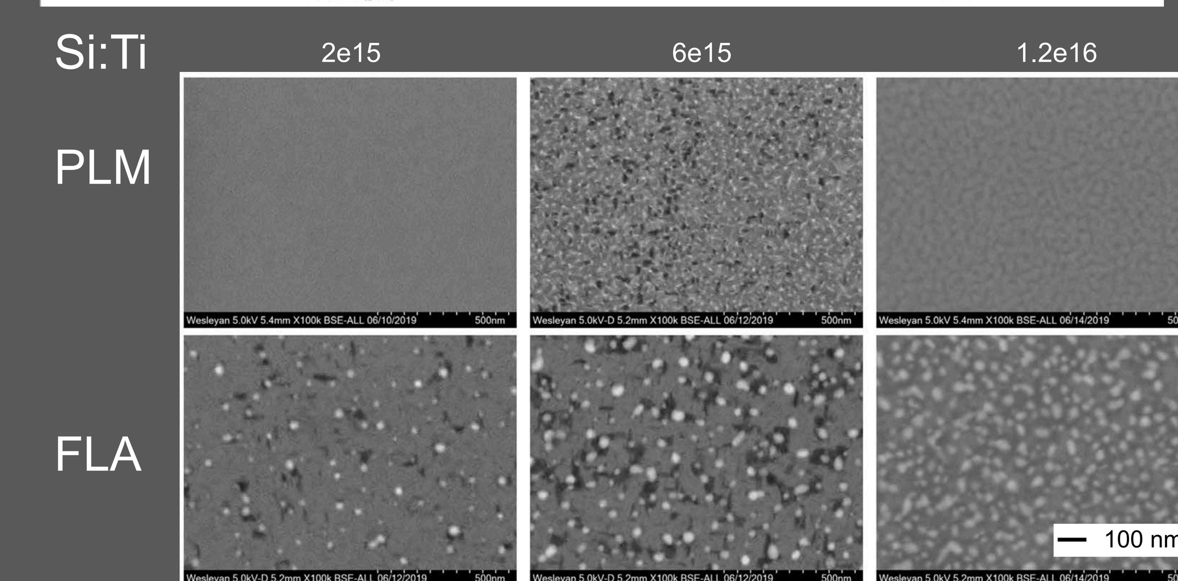
Time resolved conductivity of Ti-hyperdoped silicon is shown on the top-most plots. The Ti plots are very similar across dose and annealing method. Small differences exhibit in the lifetime (initial slope in the conductivity plot). For PLM samples, lifetime tend to increase with increasing dose, but the trend is opposite for FLA samples.

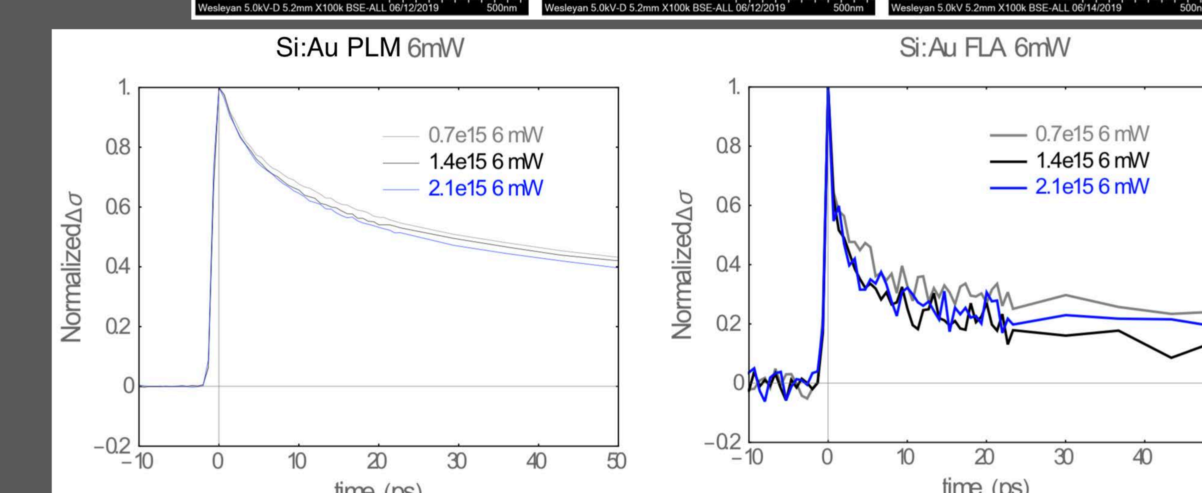
Scanning electron microscope (SEM) images show cellular breakdown occurring in the higher two concentrations of PLM samples, as well as visible Ti pockets in all FLA samples. Interestingly, they do not affect the conductivity.

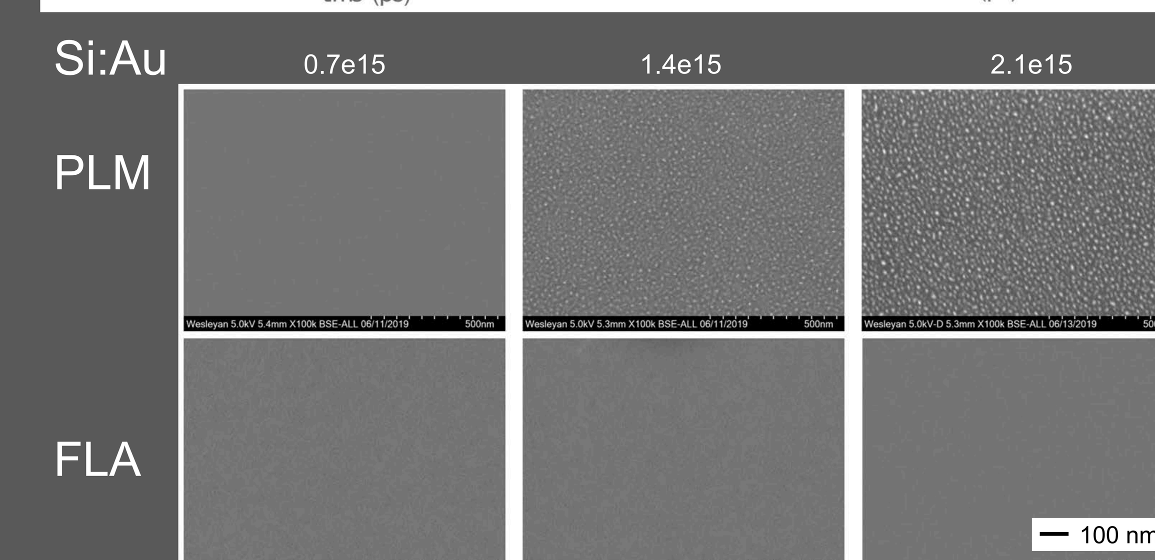
Lifetime decreases with increasing doses for both annealing methods for all Au samples. FLA samples show remarkably low lifetime and low conductivity compared to PLM samples. SEM images show Au pockets in PLM samples with increasing concentrations, but no visible trends with FLA.

Data and Images









Conclusions

- Titanium hyperdoping with PLM and FLA both show reliable performance
- PLM and FLA effectiveness depend on the dopant used
- FLA does not work with gold. It is possible that giving too much energy to Au in the hyperdoping process produces silicides ($AuSi_2$?) or interstitial complexes in the crystal that adversely affect light absorption and carrier lifetimes.