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Troy, NY 12180

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The views, opinions and/or findings contained in this report are those of the author(s) and should not contrived as an official Department of the Army position, policy or decision, unless so designated by other documentation.

14. ABSTRACT
This is a final report on an experimental research program to characterize the optoelectronic properties of very heavily sulfur doped silicon (also known as “Black Silicon”) in close collaboration with scientists at US Army Benet Labs, Harvard, and the Army Research Laboratories. Materials and devices will be prepared at Harvard. The thrusts of the proposed work were: i) to elucidate the origin of excess infrared absorption and to determine how this absorption contributes to photoresponse, and ii) to measure the transport properties of photoexcited charge.

15. SUBJECT TERMS
black silicon, hyperdoped silicon, detectors, photoconductivity

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19b. TELEPHONE NUMBER 518-276-2934
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This is a final report on an experimental research program to characterize the optoelectronic properties of very heavily sulfur doped silicon (also known as “Black Silicon”) in close collaboration with scientists at US Army Benet Labs, Harvard, and the Army Research Laboratories. Materials and devices will be prepared at Harvard. The thrusts of the proposed work were: i) to elucidate the origin of excess infrared absorption and to determine how this absorption contributes to photoresponse, and ii) to measure the transport properties of photoexcited charge carriers.

By analyzing the photoconductivity and photoresponse of coplanar and diode devices we were able to set limits on the mobility-lifetime product of sulfur-hyperdoped material. We have proposed an excitation and charge separation mechanism that is consistent with all data.

Enter List of papers submitted or published that acknowledge ARO support from the start of the project to the date of this printing. List the papers, including journal references, in the following categories:

(a) Papers published in peer-reviewed journals (N/A for none)

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TOTAL: 4

Number of Papers published in peer-reviewed journals:

(b) Papers published in non-peer-reviewed journals (N/A for none)
(c) Presentations


Photocarrier Excitation and Transport in Hyperdoped Planar Silicon Devices, Peter D. Persans1, Nathaniel Berry1, Daniel Recht2, David Hutchinson1, Aurore Said2, Jeffrey Warrender3, Hannah Peterson1,3, Anthony DiFranzo1, Christina McGahan1, Jessica Clark1, Will Cunningham1, Michael Aziz2, MRS Symposium A Poster, April 2011.


Number of Presentations: 7.00

Non Peer-Reviewed Conference Proceeding publications (other than abstracts):

Peer-Reviewed Conference Proceeding publications (other than abstracts):
Number of Peer-Reviewed Conference Proceeding publications (other than abstracts):

**(d) Manuscripts**

Received Paper

08/01/2012  6.00 Peter D. Persans, Nathaniel E. Berry, Daniel Recht, David Hutchinson, Hannah Peterson, Jessica Clark, Supakit Charnvanichborikarn, James S. Williams, Anthony DiFranzo, Michael J. Aziz, Jeffrey M. Warrender. Photocarrier Lifetime and Transport in Silicon Supersaturated with Sulfur, Applied Physics Letters (04 2012)

TOTAL: 1

Number of Manuscripts:

**Books**

Received Paper

TOTAL:

**Patents Submitted**

**Patents Awarded**

**Awards**
### Graduate Students

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### Student Metrics

This section only applies to graduating undergraduates supported by this agreement in this reporting period.

- The number of undergraduates funded by this agreement who graduated during this period: **6.00**
- The number of undergraduates funded by this agreement who graduated during this period with a degree in science, mathematics, engineering, or technology fields: **6.00**
- The number of undergraduates funded by your agreement who graduated during this period and will continue to pursue a graduate or Ph.D. degree in science, mathematics, engineering, or technology fields: **6.00**
- Number of graduating undergraduates who achieved a 3.5 GPA to 4.0 (4.0 max scale): **6.00**
- Number of graduating undergraduates funded by a DoD funded Center of Excellence grant for Education, Research and Engineering: **0.00**
- The number of undergraduates funded by your agreement who graduated during this period and intend to work for the Department of Defense: **0.00**
- The number of undergraduates funded by your agreement who graduated during this period and will receive scholarships or fellowships for further studies in science, mathematics, engineering or technology fields: **6.00**
### Names of Personnel receiving masters degrees

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<td>David Hutchinson</td>
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Total Number: 3

### Names of personnel receiving PHDs

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### Names of other research staff

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Sub Contractors (DD882)

Inventions (DD882)
The goal of the proposed work was to measure and elucidate photocarrier excitation and recombination processes and parameters in heavily doped S:Si prepared by implantation and pulsed laser melting. Fundamental parameters such as free carrier diffusion lengths, mobility, drift mobility, free carrier lifetime, and decay time were to be extracted from photoconductivity, steady state photocarrier grating, and photosresponse measurements. We developed techniques for measurement and analysis of coplanar photoconductivity response spectra for the extraction of minority carrier diffusion lengths and photocarrier lifetimes in thin layers. This allowed us to set limits on the carrier mobility and lifetimes in Si hyperdoped with chalcogens.

We characterized the photodetection efficiency spectral response of n+/p diodes based on S-hyperdoped Si and established that normal response is due to carriers generated in the depletion region in the normally doped Si substrate. The hyperdoped region creates a good-quality high-conductivity contact layer and a rectifying junction with the substrate. Collection efficiency in the near infrared is of order 0.5, dropping off dramatically beyond 1100 nm wavelength.

We observed very high gain photosresponse in regions of some diode devices based on n+/p junctions. The current working model is that high gain is due to modification of the n+/p barrier by trapped photocarriers, allowing majority carriers from the p-region to flow through the junction. Further work is underway to identify the origin, reproducibility, and utility of this high gain behavior.

We developed a photosponse mapping system that enabled us to identify the scope of high gain regions.

We developed techniques for measuring optical absorptance in thin layers using photothermal deflection spectroscopy and were able to confirm that transmission and spectroscopic ellipsometry measurements of IR absorption in hyperdoped layers were reliable.

We developed contactless microwave and contacted coplanar techniques to measure transient photoconductivity of n+/p and n+ SOI layers. Initial results confirmed lifetimes inferred from steady state measurements. Recent measurements in collaboration with Jeff Warrender at Benet Labs indicate that we will be able to directly measure lifetimes for UV and IR excitation of thin layers hyperdoped with S, Se, Au, Ti, and other novel dopants.

In addition to our specific published work to measure general properties of hyperdoped materials, we performed regular characterization of hundreds of new materials and devices fabricated at Benet Laboratories and Harvard University with assistance from the Buonassissi group at MIT.

Our observation of high gain in S:Si and Se:Si based n+/p diodes led to an increased focus on these devices. A preliminary paper has been published in Applied Physics Letters. The analysis of the spatial size, voltage dependent gain, and wavelength dependent response including 5 micron-scale resolution maps has formed the basis for an MS thesis. The project was led by Prof. Peter Persans. Three graduate students participated in this project resulting in two MS projects (Thomas Cruson and Brett Spencer) and one MS thesis (David Hutchinson). David Hutchinson is continuing to work on an extension of this project for his PhD thesis. A fourth MS student, Colonel Alex Katauskas, will complete his degree work in May 2013. Colonel Katauskas will take up a position at West Point after completing his work with us. We expect that he will continue to collaborate with us while he is posted at West Point.

Aurora Said and Daniel Recht of Harvard University and Jeff Warrender of ARDEC spent several days each in our laboratories carrying out measurements.

Several undergraduate students participated in this project, including senior students Nathaniel Berry, Nikolina Bohr, Jessica Clark, Anthony DiFranzo, Andrew McAllister, Christina McGahan, and Hanna Peterson, and junior students James Cotter, William Cunningham, Chris Fuller, James Ladouce, Mark Millman, Drew Rosen, and David Lombardo. Although this contract supplied partial support for many of these students, significant funding was provided by the NSF REU program, the NSF GK12 program, and the Graduate Teaching Assistantship and Undergraduate Research programs at Rensselaer.

Technology Transfer