AIP Advances
CELEBRATING 5 YEARS

Photocurrent response of B12As2 crystals to blue light, and its temperature-dependent electrical characterizations

R. Gul, Y. Cui, A. E. Bolotnikov, G. S. Camarda, S. U. Egarievwe, A. Hossain, U. N. Roy, G. Yang, J. H. Edgar, U. Nwagwu, and R. B. James

Citation: AIP Advances **6**, 025206 (2016); doi: 10.1063/1.4941937
View online: http://dx.doi.org/10.1063/1.4941937
View Table of Contents: http://scitation.aip.org/content/aip/journal/adva/6/2?ver=pdfcov
Published by the AIP Publishing

AIP ADVANCES **6**, 025206 (2016)

Photocurrent response of $B_{12}As_2$ crystals to blue light, and its temperature- dependent electrical characterizations

R. Gul,[1,2,a] Y. Cui,[1] A. E. Bolotnikov,[1] G. S. Camarda,[1] S. U. Egarievwe,[2] A. Hossain,[1] U. N. Roy,[1] G. Yang,[1] J. H. Edgar,[3] U. Nwagwu,[3] and R. B. James[1]
[1]*Brookhaven National Laboratory, Upton, NY, 11973, USA*
[2]*Alabama A&M University, Normal AL, 35762, USA*
[3]*Kansas State University, Manhattan, KS, 66506, USA*

(Received 24 November 2015; accepted 27 January 2016; published online 9 February 2016)

With the global shortage of ^{3}He gas, researchers worldwide are looking for alternative materials for detecting neutrons. Among the candidate materials, semiconductors are attractive because of their light weight and ease in handling. Currently, we are looking into the suitability of boron arsenide ($B_{12}As_2$) for this specific application. As the first step in evaluating the material qualitatively, the photo-response of $B_{12}As_2$ bulk crystals to light with different wavelengths was examined. The crystals showed photocurrent response to a band of 407- and 470- nm blue light. The maximum measured photoresponsivity and the photocurrent density at 0.7 V for 470 nm blue light at room temperature were 0.25 A·W^{-1} and 2.47 mA·cm^{-2}, respectively. In addition to photo current measurements, the electrical properties as a function of temperature (range: 50-320 K) were measured. Reliable data were obtained for the low-temperature I-V characteristics, the temperature dependence of dark current and its density, and the resistivity variations with temperature in $B_{12}As_2$ bulk crystals. The experiments showed an exponential dependence on temperature for the dark current, current density, and resistivity; these three electrical parameters, respectively, had a variation of a few nA to μA, 1-100 μA·cm^{-2} and 7.6x10^5-7.7x10^3 Ω·cm, for temperature increasing from 50 K to 320 K. The results from this study reported the first photoresponse and demonstrated that $B_{12}As_2$ is a potential candidate for thermal-neutron detectors. [http://dx.doi.org/10.1063/1.4941937]

I. INTRODUCTION

The release of radioactive materials presents a real threat to homeland- and national-security. Neutron detectors are important to detecting and safeguarding fissile- and radioactive-materials because they often emit neutrons that may be difficult to hide by shielding. The most common neutron detectors are ^{3}He-based gas counters. However, their use is limited by the weight and cost of the pressure vessels that contain the gas; furthermore, they are relatively delicate and hence difficult to use in the field. These problems are compounded greatly by the recent shortage of ^{3}He gas. Alternative detectors are based on the high-reaction cross-sections of a few isotopes, particularly ^{10}B and ^{6}Li, which absorb neutrons and generate charged particles as a by-product, typically alphas; in turn, these create mobile charges via ionization in a medium and generate a current pulse that can be measured and recorded. Among them, solid-state materials are especially appealing in view of their compact size, easy maintenance, few restrictions on shipping, and potentially low cost. Boron-containing compound semiconductors especially are good candidates because the ^{10}B isotope has a large thermal neutron capture cross-section (3840 barns),[1] and it is abundant, 20% of

[a]Author to whom correspondence should be addressed. Rubi Gul Electronic mail: rubi786@yahoo.com

natural boron. In addition, in such compound materials, neutron capture and ionization generation occur in the same media, allowing full absorption of secondary particles and, ideally, complete charge collection of the generated electrons and holes. Among all the candidate semiconductor materials, icosahedral boron arsenide ($B_{12}As_2$) particularly is appealing for thermal neutrons detection due to its wide band-gap (3.20-3.47 eV)[2–5] and potentially good carrier-transport properties.

As our first step in assessing $B_{12}As_2$ material for radiation detection, we measured its optical properties especially the photocurrent response to a short-wavelength LED and low-temperature electrical properties. This study was intended to explore, and hopefully validate, that the charge carriers in $B_{12}As_2$ could be activated by incident LED-energy and transported through the crystal inducing electronic signals on the electrodes of fabricated detectors that could be measured by an appropriate readout circuit.

II. EXPERIMENTAL DETAILS

$B_{12}As_2$ bulk crystals in this research were grown by precipitation from molten-metal solutions as described previously by Whiteley et al.[6] In brief, boron was dissolved in molten nickel at 1150 °C then reacted with arsenic vapors to produce dissolved $B_{12}As_2$. Bulk crystals were formed as the solution slowly cooled down. $B_{12}As_2$ bulk material, with an area of 3 mm^2 and with 1-mm thickness was used to fabricate a planer detector. Ohmic contacts were fabricated by affixing a few micron thick silver metal spot on both planar surfaces of a $B_{12}As_2$ bulk crystal. The diameter of the silver contact was ~2 mm.

Samples were mounted in a closed-cycle He cryostat system for measurements both at low temperature and above room temperatures. The temperature controller has an error of < 0.1K in stabilizing and recording a particular temperature. The system offered a dark chamber under high vacuum atmosphere, which minimized surrounding effects in measuring the nano-Ampere currents. The details of equipment and electronics are described elsewhere.[7] To make measurements the detector was mounted on the vertical cold finger in the cryogenic system with a positive bias applied on to the back of the crystal.

In the photo-response experiments, the crystal was illuminated from the front with light of different wavelengths, i.e., 407-, 470-, 630-, and 822- nm LEDs, with power range of ~ 4-6 mW. Different voltages ranging from 0.01-0.7 V were applied across the detectors. At each bias setting, the sample was cooled down to 280 K, and then heated up to 310 K in a step of 3 K.; data were collected at each temperature setting. In the low-temperature electrical characterization, the sample was cooled down to 50 K and heated up to 320K in a step of 1 ± 0.1K.

III. RESULTS AND DISCUSSION

A. Photo Response of the $B_{12}As_2$ bulk crystals

The $B_{12}As_2$ crystal demonstrated a photo-response to light of 407 nm (3.05 eV) and 470 nm (2.64 eV). An analysis of the induced photocurrents vs. the power of the 470-nm LED is shown in Fig. 1; the photocurrent increases linearly with the light's incident power. The photoresponsivity determined by the photocurrent data and the incident power of the LED of 407- and 470-nm was tested at different applied biases (Fig. 2). At 470 nm the response (0.25 AW^{-1}) is almost two and a half-fold greater than to the 407 nm (0.10 AW^{-1}) light. The lower photo-response to the later might be because of the low output power of 407-nm LED. For lights with higher wavelengths, the penetration depths are higher than the thickness of the detector and hence, material was almost transparent to the higher wavelengths and hence, there was no photo response. Figure 3 illustrates the photocurrent increases linearly with the increase in temperature from 280 K to 320 K. Comparing the four plots in Fig. 3. a gradual shift in photo current is observed with the increased bias; while the photo-response is less than an order-of-magnitude, from the dark current.

The temperature- and bias- dependence of photo-responsivity was also studied. It is evident that the responsivity of the detector increases by a fraction of AW^{-1} with a temperature rise of 10-15 K (Fig. 4) that is not significant but cannot be ignored. The rate is smaller near room temperature (RT).

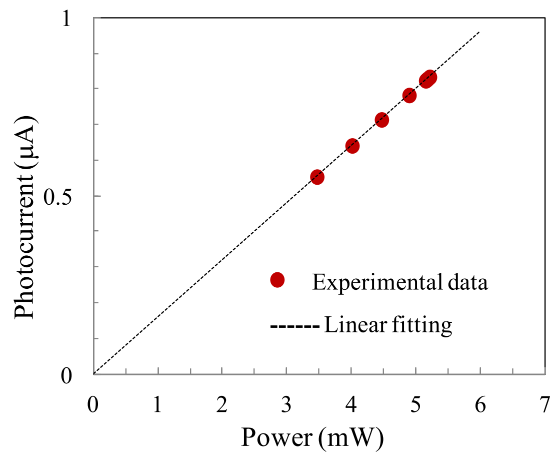

FIG. 1. Linear variation of the Photocurrent with the increasing power of the 470- nm LED.

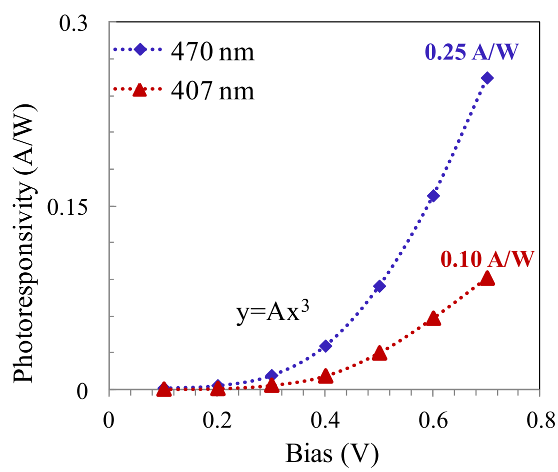

FIG. 2. Photoresponsivity measured for $B_{12}As_2$ crystals for 407- and 470-nm blue LED light at different applied voltages, at room temperature.

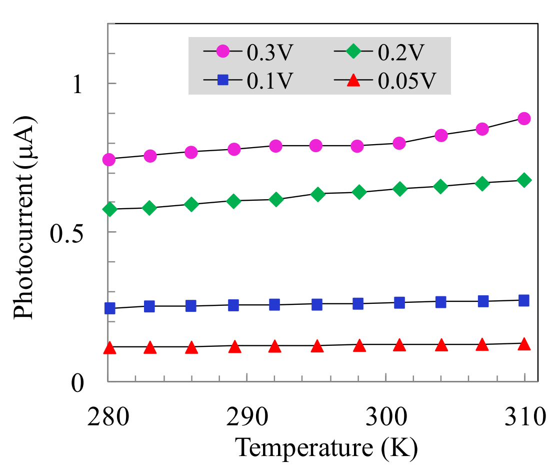

FIG. 3. Temperature dependence of photocurrent response of $B_{12}As_2$ crystals to 470-nm blue LED- light and the corresponding dark current at different applied voltages.

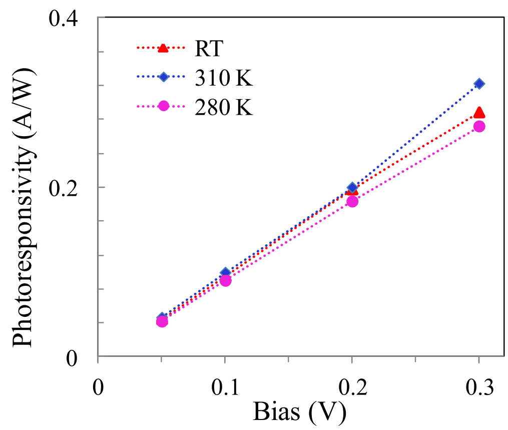

FIG. 4. Temperature dependence of photoresponsivity measured for $B_{12}As_2$ crystals for 470-nm blue LED light; at RT, and 20K above and below RT.

The value at RT, i.e., 0.28 AW^{-1}, remains constant for RT±5 K; furthermore, the slope of the curves above and below this specific temperature-region are different (Fig. 5), indicating that rate of change of photoresponsivity with temperature below RT is lower than that above RT.

B. Low-temperature Electrical Characterizations

The electrical properties of $B_{12}As_2$ crystals were investigated at temperature of 50-320 K with applied bias from 0.01 to 0.7 V. The temperature dependence of the leakage current is shown as current-temperature (I-T) plots in Fig. 6. The dark current increases exponentially with the increase of temperature. Here, the current's gradient dI(T)/dT, is higher at above RT than that below RT. The temperature dependence of current-voltage (I-V) characteristics is also shown in Fig. 7. The leakage current at RT is almost double of that at the lowest measured temperature of 50 K. The calculated current densities indicate that high value of current density (0.10 mA-cm^{-2} @ 320K) is attributed to the highest measured temperature. The value drops to 0.07 mA-cm^{-2} at room temperature.

The bulk resistivity calculated from the I-V curves plotted in Fig. 8 indicates that resistivity follows an exponentially decreasing path. The fitting function in plot indicates that the resistivity changes by a temperature- dependent factor of e^{-bT}. Resistivity at 50K has its highest value of $7.6x10^5$ Ω·cm, and it drops by two orders to $1x10^4$ Ω·cm at room temperature; on further heating it reaches to its lowest value of $7.7x10^3$ Ω·cm at 320K. from Similar experiment at higher temperature was also reported by Frye et al.[8]

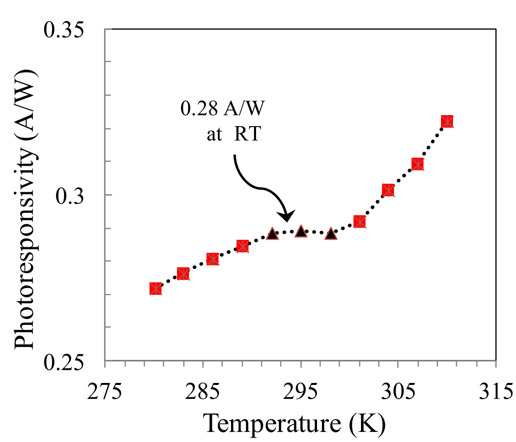

FIG. 5. Temperature dependence of photoresponsivity of a $B_{12}As_2$ crystals towards 470-nm light at 0.3 eV.

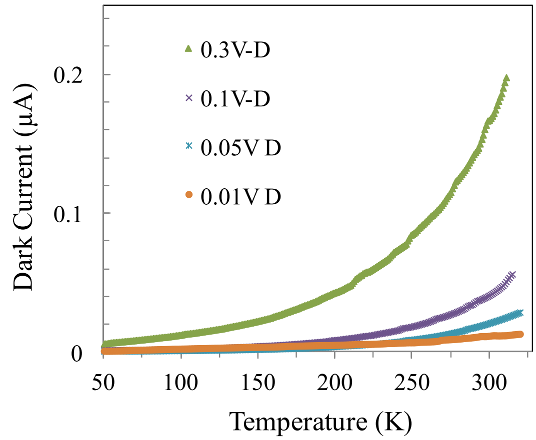

FIG. 6. Dark current measurements for $B_{12}As_2$ crystals and its temperature dependence at different applied voltages.

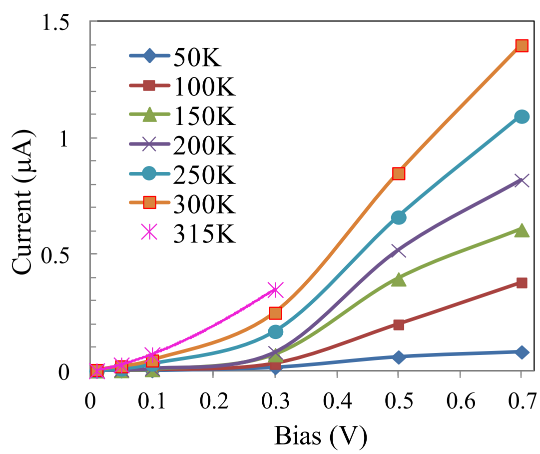

FIG. 7. Temperature dependence of I-V characteristic plots for $B_{12}As_2$ crystals.

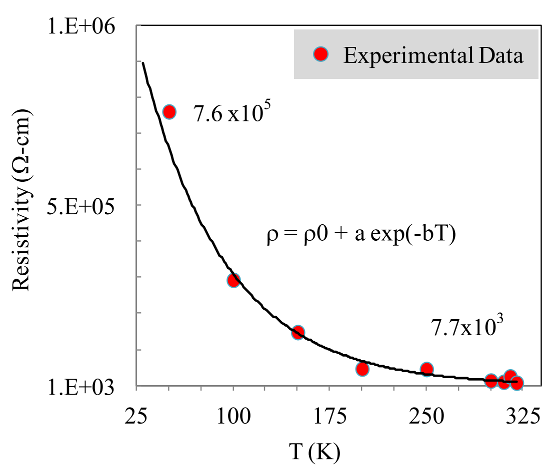

FIG. 8. Resistivity of the $B_{12}As_2$ crystals and its temperature dependence.

IV. CONCLUSIONS

In this paper, we detailed our studies of the photo-responses and electrical properties of $B_{12}As_2$ crystals grown by precipitation from molten metal. The crystals showed a photo-response to blue

(470- and 407-nm) light. This response, an important finding, suggests that $B_{12}As_2$ may be a potential material for applications in radiation detection, especially for thermal-neutron detection. The leakage current of the material decreases at lower temperature; above room temperature, it abruptly increases with temperature due to thermally generated carriers. These detectors are operable at room temperature and below it for low applied bias, less than 1V. The resistivity of the crystals at room temperature is $1.4\text{x}10^4\ \Omega\cdot\text{cm}$; this value increases exponentially with decreasing temperature. Electrical properties including leakage current, current density and resistivity, are studied and reported as function of temperature. The data can be used by crystal growers to improve the quality of ($B_{12}As_2$) crystals, particularly to increase the crystal's resistivity thereby to lower the noise in the detectors to a level appropriate for measuring single neutron.

ACKNOWLEDGEMENTS

This research is supported by Laboratory Directed Research and Development (LDRD) program at Brookhaven National Laboratory. Authors are thankful to Dr. Thomas Tsang from Instrumentation Department, for his technical support and discussions.

[1] V. F. Sears, Neutron News **3**, 26 (1992).
[2] S. Bakalova, Y. Gong, C. Cobet *et al.*, Phys. Rev. B **81**, 075114 (2010).
[3] G. A. Slack, T. F. McNelly, and E. A. Taft, J. Phys. Chem. Solids **44**, 1009 (1983).
[4] P. B. Klein, U. Nwagwu, J. H. Edgar *et al.*, Journal of Applied Physics **112**, 013508 (2012).
[5] H. Chen, G. Wang, M. Dudley *et al.*, Appl. Phys. Lett **92**, 231917 (2008).
[6] C. E. Whiteley, "Advanced Crystal Growth Techniques with III-V Boron Compound Semiconductors," Ph.D. thesis, Kansas State University, 2011.
[7] R. Gul, R. B. James, K. H. Kim *et al.*, Journal of Electronic Materials **40**(3), 274 (2011).
[8] C. D. Frye, J. H. Edgar, I. Ohkubo *et al.*, Journal of the Physical Society of Japan **82**, 095001 (2013).