

Provided for non-commercial research and education use.  
Not for reproduction, distribution or commercial use.



This article appeared in a journal published by Elsevier. The attached copy is furnished to the author for internal non-commercial research and education use, including for instruction at the authors institution and sharing with colleagues.

Other uses, including reproduction and distribution, or selling or licensing copies, or posting to personal, institutional or third party websites are prohibited.

In most cases authors are permitted to post their version of the article (e.g. in Word or Tex form) to their personal website or institutional repository. Authors requiring further information regarding Elsevier's archiving and manuscript policies are encouraged to visit:

<http://www.elsevier.com/copyright>



Contents lists available at ScienceDirect

## Solid State Communications

journal homepage: [www.elsevier.com/locate/ssc](http://www.elsevier.com/locate/ssc)

## Rapid photoresponse of single-crystalline selenium nanobelts

Aimiao Qin<sup>a,b</sup>, Zhou Li<sup>b,c</sup>, Rusen Yang<sup>b</sup>, Yudong Gu<sup>b,c</sup>, Yuzi Liu<sup>b</sup>, Zhong Lin Wang<sup>b,\*</sup><sup>a</sup> Key Laboratory of New Processing Technology for Nonferrous Metals and Materials, Ministry of Education, Department of Materials and Chemistry Engineering, Guilin Institute of Technology, Guilin, 541004, China<sup>b</sup> School of Materials Science and Engineering, Georgia Institute of Technology, Atlanta, GA 30332, USA<sup>c</sup> Department of Advanced Materials and Nanotechnology, College of Engineering, Peking University, Beijing, 100871, China

## ARTICLE INFO

## Article history:

Received 1 July 2008

Accepted 20 July 2008 by A.H. MacDonald

Available online 26 July 2008

## PACS:

72.40.+w

## Keywords:

A. Nanobelt

A. Se

D. Photoconductivity

## ABSTRACT

Rapid photon response is demonstrated for devices made using individual single-crystalline selenium nanobelts. The temperature dependence of the photocurrent has been studied between  $-70$  to  $100$  °C. The best performance is at temperatures below  $40$  °C. The response time to fluorescent light is as quick as  $30$  ms once tunes on, and the recovery time is as short as  $50$  ms when the light is off. This study demonstrates the potential application of Se nanobelts for building fast photon detectors.

© 2008 Elsevier Ltd. All rights reserved.

## 1. Introduction

In the past decade, one-dimensional (1-D) nanostructures such as rods, wires, belts, ribbons and tubes have become the focus of intensive research owing to their fascinating applications in mesoscopic physics and nanodevices. Selenium, as an important elemental semiconductor, is widely used in photocells, photographic exposure meters, xerography, pressure sensors and electrical rectifier due to its high photoconductivity and large piezoelectric, thermoelectric and nonlinear responses [1–7]. On the photoconductivity of selenium, most previous research has mainly focused on amorphous selenium and hexagonal metallic selenium film or bulk materials. Recently, much work has been concentrated on the synthesis of 1-D selenium nanostructures such as nanowires [8,9], nanorods [10], nanotubes [11], nanoribbons [12] and nanobelts [13]. However, there is limited study available on the physical properties of the Se nanostructures, especially as photonic or electrical devices [14]. Here we report a study about ultrafast photon response of trigonal selenium nanobelts fabricated by a facile and large-scale synthesis method. The devices made using individual nanobelts have a fast response to visible light illumination, with potential as fast photon sensors and photo-cells.

## 2. Experiment

All of chemicals used for the synthesis were of analytical grade and used as received without further purification. Single-crystalline  $t$ -Se nanobelts were synthesized by solvothermal method. A typical experimental procedure is described as following.  $1.3$  mmol ( $0.1$ g) Se and  $17$  ml ethanol were loaded into Teflon-lined autoclave of  $25$  mL capacity. The autoclave was sealed and maintained at  $200$  °C for  $24$  h. Then the autoclave was taken out and cooled to room temperature, the precipitates were filtered off and washed with absolute alcohol for several times and dried naturally.

The as-synthesized products were characterized and analyzed by X-Ray Diffraction (XRD, Alpha-1) using CuK $\alpha$  radiation, Field Emission Scanning Electron Microscope (FE-SEM, Leon 1530) equipped with an Energy Dispersive X-Ray Spectroscopy (EDX) and transmission electron microscopy (TEM, HF-2000).

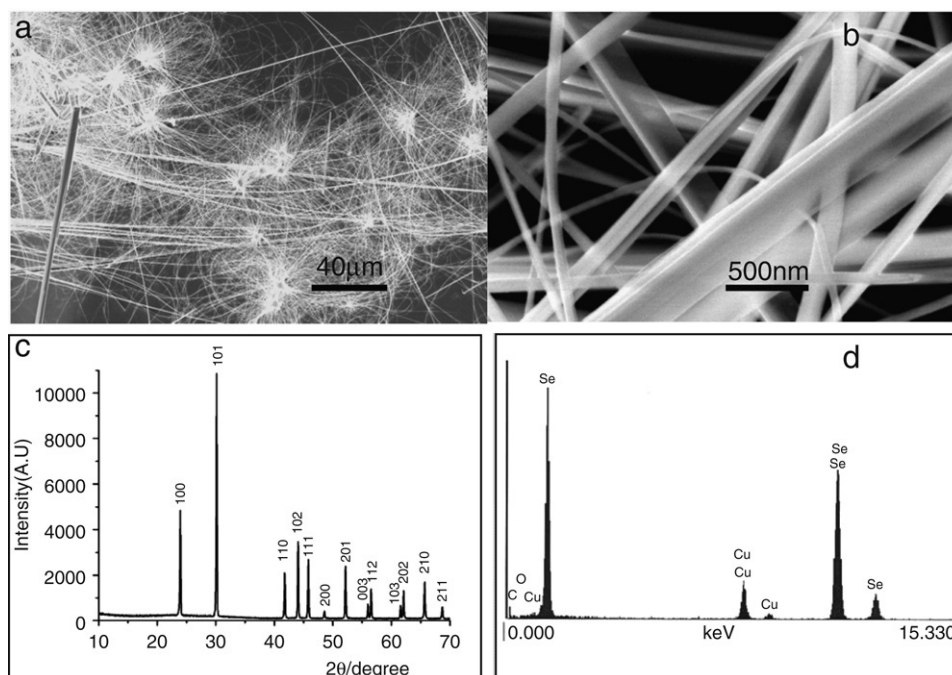
Electrical transport measurement was conducted based on devices made using single nanobelts. A single selenium nanobelt was aligned on glass slide or thermally grown silicon oxide substrate with cleaned surfaces. The electrical contacts were prepared by applying highly conductive silver paint through suitable masks. This is possible because the nanobelts are rather long.

## 3. Results and discussion

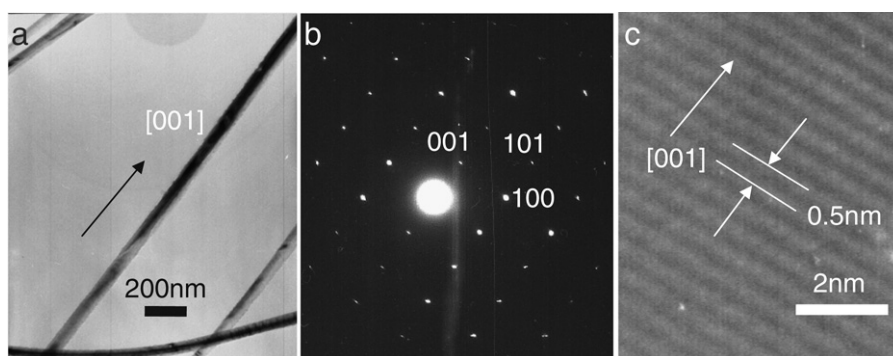
Fig. 1(a, b) show low-magnification and high-magnification scanning electron microscopy images of the  $t$ -Se nanobelts.

\* Corresponding author. Tel.: +1 4048948008; fax: +1 4048948008.

E-mail address: [zlwang@gatech.edu](mailto:zlwang@gatech.edu) (Z.L. Wang).



**Fig. 1.** (a) and (b) SEM images of single-crystalline Se nanobelts grown by a solvothermal method (c) XRD pattern of Se nanobelts confirms the trigonal structure, (d) EDS of Se nanobelts shows the pure composition.



**Fig. 2.** Electron diffraction pattern and HRTEM of a typical Se nanobelt. (c) HRTEM image taken from the middle of the Se nanobelt (a) with growth direction [001], showing its single-crystalline structure. The corresponding electron diffraction pattern (b) was obtained from the same Se nanostructure.

The nanobelt sizes range from 100 to 500 nm and lengths range from tens to hundreds of micrometers. XRD from the sample confirms the structure is trigonal (Fig. 1(c)). Chemical analysis using energy-dispersive X-ray spectroscopy (EDS) shows the pure composition of Se (Fig. 1(d)). Transmission electron microscopy (TEM) study (Fig. 2) further confirms that the t-Se nanobelts have single-crystal structure with growth direction [001].

The photoconductivity measurements were first performed using room light (fluorescent lamp) at room temperature at ambient pressure. In order to investigate the temperature effect on the photon sensitivity, we have carried out experiments at different temperatures, and the results are presented in Fig. 3(a). Under an applied voltage of 1 V, it is observed that the current transported through a single nanowire drastically increases by a factor of 10 when the light was turned on. The photoconductivity is mainly determined by the recombination and trapping of the electron-hole pairs within a solid material, and the rate of such a recombination and trapping for selenium has been shown to strongly depend on temperature [15,16]. In general, the conductivity increases as temperature rises. Generally, trigonal selenium is accepted as a p-type extrinsic semiconductor, and conduction occurs due to valence band hole transport [16].

The increased thermal conductivity is likely due to the thermal excitation of the electron-hole pairs in the valence band as governed by  $\exp(-E_g/KT)$ , where  $E = 1.6$  eV (770 nm) is the bandgap of Se,  $K$  is Boltzmann constant and  $T$  is temperature.

The photosensitivity, defined as  $S = (I - I_0)/I_0$ , where  $I$  and  $I_0$  are the currents measured when the light is on and off, respectively, is strongly affected by temperature.  $S$  drops as temperature increases (Fig. 3(b)). The best photosensitivity is received at temperatures lower than 40 °C. The carriers are contributed by thermal excitation and photon excitation. With the increase of temperature, the thermal excitation is enhanced, thus, the photosensitivity is relatively reduced.

The response time of the Se nanobelt to visible light is characterized by the rising and falling shape of the photocurrent curve. Fig. 4(a) and (b) show the sensitivity response to light at room temperature, the increasing and the decay response times are about 30 and 50 ms, respectively, as measured at the half maximum.

In order to investigate the photon sensitivity of the t-Se nanobelt to light of different wave lengths, the photocurrent is measured with a chopped light (75 Watt xenon lamp) of wavelengths selected in the range from 300 to 800 nm. It is found

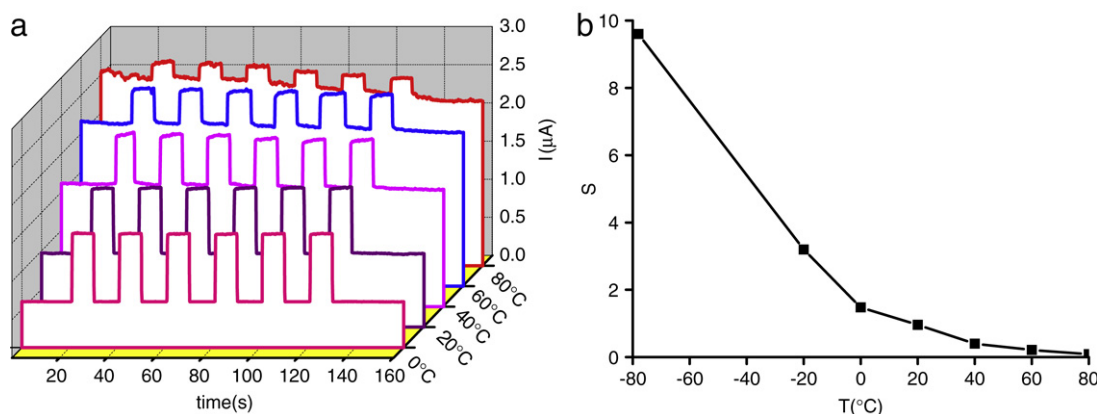


Fig. 3. Temperature dependence of (a) photoconductivity and (b) photosensitivity of a Se nanobelt based device.

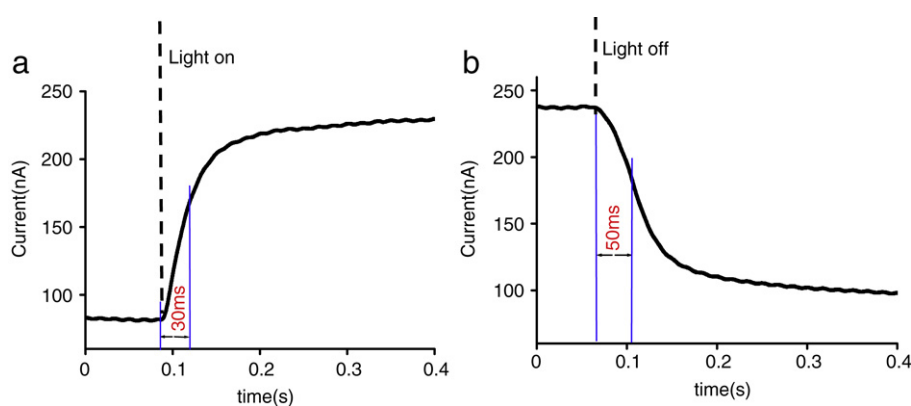


Fig. 4. (a) Response and (b) recovery of a Se nanobelt based device when a fluorescent light was turned on and off, respectively, at room temperature.

that the higher response is observed in the visible wavelength range, which is in agreement with the previous report [4]. However, monochromatic light of 350 nm has a faster response (0.140 s for light on and 0.2 s for light off) than that of 550 nm (0.185 and 0.229 s) and 650 nm (0.186 and 0.238 s) light. The fluorescent lamp exhibit the quickest response (0.03 s and 0.05 s). According to the reference, the fluorescent lamp has higher photoconductivity and faster response speed could be attributed to a broader spectral overlap of the source with the region of maximum photoconductive response of t-Se. The maximum photoconductive response for our single-crystalline t-Se nanobelt is at  $\sim 550$  nm, which is a little different from that previously reported of 650 nm at  $-190$  °C and 750 nm at 20 °C [17].

#### 4. Conclusion

In summary, rapid photon response and high photon sensitivity of single-crystalline Se nanobelt have been observed. The responses of Se nanobelt to fluorescent light at 25 °C are 30 and 50 ms when the light is turned on and off, respectively. The highest photon sensitivity is obtained at low temperatures. This study demonstrates the potential of using Se nanobelts as rapid response photo-sensors and photo-cells.

#### Acknowledgements

This work was supported under the NSF of Guangxi Zhuang Autonomous Region (0640068), the Science Foundation of Guangxi Education (200508043), USA DOE BES (DE-FG02-07ER46394) and NSF (DMS 0706436).

#### References

- [1] J.A. Johnson, L.M. Sabongi, D.J. Meisel, *J. Phys. Chem. B* 103 (1999) 59.
- [2] R.A. Zingaro, W.C. Cooper (Eds.), *Selenium*, Van Nostrand Reinhold, New York, 1974.
- [3] L.I. Berger, *Semiconducting Materials*, CRC Press, Boca Raton, FL, 1997.
- [4] B. Gates, B. Mayers, A. Grossman, Y. Xia, *Adv. Mater.* 14 (2002) 1749.
- [5] B. Gates, B. Mayers, B. Cattle, Y. Xia, *Adv. Funct. Mater.* 12 (2002) 219.
- [6] H.T. Li, P.J. Regensburger, *J. Appl. Phys.* 34 (1963) 1730.
- [7] U.K. Gautam, M. Nath, C.N.R. Rao, *J. Mater. Chem.* 13 (2003) 2845.
- [8] B. Mayers, K. Liu, D. Sunderland, Y. Xia, *Chem. Mater.* 15 (2003) 3852.
- [9] B. Gates, B. Mayers, B. Cattle, Y. Xia, *Adv. Funct. Mater.* 12 (2002) 219.
- [10] J.M. Song, J.H. Zhu, S.H. Yu, *J. Phys. Chem. B* 110 (2006) 23790.
- [11] Y.R. Ma, L. Qi, J. Ma, H. Cheng, *Adv. Mater.* 16 (2004) 1023.
- [12] X. Cao, Y. Xie, S. Zhang, F. Li, *Adv. Mater.* 16 (2004) 649.
- [13] Q. Wang, G.D. Li, Y.L. Liu, S. Xu, K.J. Wang, J.S. Chen, *J. Phys. Chem. C* 111 (2007) 12926.
- [14] P. Liu, Y. Ma, W. Cai, Z. Wang, J. Wang, L. Qi, D. Chen, *Nanotechnology* 18 (2007) 205704.
- [15] W.E. Spear, *J. Phys. Chem. Solids* 21 (1961) 110.
- [16] M.A. Gilleo, *J. Chem. Phys.* 19 (1951) 1291.
- [17] D.S. Elliott, *Phys. Rev.* 5 (1915) 53.