

# The effect of cryogenic temperature treatment (77K) on silicon for photodetector applications

M. Z. MOHD YUSOFF<sup>a,b,\*</sup>, M. R. HASHIM<sup>a</sup>

<sup>a</sup>*Nano-Optoelectronics Research and Technology Laboratory, School of Physics, Universiti Sains Malaysia, 11800 Penang, Malaysia*

<sup>b</sup>*Department of Applied Sciences, Universiti Teknologi MARA (UiTM), 13500 Permatang Pauh, Penang, Malaysia*

The purpose of this paper is to describe a very low-cost way to get low dark current metal-semiconductor-metal (MSM) photodetector. The application of cryogenic temperature treatment (77 K) at various cooling times (15-60 min) has been shown to significantly modify the surface properties of n-type silicon (100). Fresh monocrystalline n-type silicon (100) with a resistivity of 10-16 ohm-cm was used for the study. The Si was dipped in liquid nitrogen for 15 to 60 minutes at atmospheric pressure. The sample was folded in Al foil to avoid direct contact with liquid nitrogen. The surface roughnesses of the untreated and treated samples were determined by using AFM. The nickel (Ni) metal contacts were then deposited on the samples followed by current-voltage characterization (I-V). Optical properties of our samples were determined by Raman spectroscopy and XRD measurement at room temperature. Treated Si samples have better surface uniformity than untreated samples. The treated samples showed significant decrease in dark and light currents compared with the untreated samples. The current gain (ratio of photo to dark current) of some of the treated samples is enhanced whereas some are reduced compared with that of the untreated samples. The results showed that the treated samples have both higher Raman and XRD intensities than the untreated samples. This paper shows that it is possible to get smooth surface of silicon by using a simple and low-cost method of cryogenic temperature treatment and demonstrates potential MSM photodetector IV characteristics from the device.

(Received August 1, 2011; accepted October 20, 2011)

**Keywords:** Cryogenic processing, Liquid nitrogen, Photodetector, MSM, silicon

## 1. Introduction

The planar Si metal-semiconductor-metal (MSM) photodetector is one of the most promising candidates for receiver optoelectronic integrated circuits (OEICs) owing to the ease of fabrication, low capacitance per unit area, and ease of integration with preamplifier circuit (Chui *et al.*, 2003; Laih *et al.*, 1997). However, most simple Si MSM photodetectors have a high dark current and a large transient fall time. In the past, to improve the transient response, many methods such as ion-implantation of the absorbing layer or reduction of the spacing between interdigitated electrodes were suggested. Ion-implantation is an expensive process (Sharma *et al.*, 1994) and an electrode with a small spacing would retard incident light and is difficult to fabricate (Liu *et al.*, 1995).

Previous studies (Shi *et al.*, 1991; Shi *et al.*, 1992; Lee *et al.*, 1993; He *et al.*, 1994; Wang *et al.*, 1995; Clark *et al.*, 1996; Palmer *et al.*, 1996; He, 1997; Cammack *et al.*, 1998; Hong and Anderson, 1999; He and Siewenie, 2002; Hashim *et al.*, 2004; Lee *et al.*, 2005; Li and Anderson, 2005; Hashim and Salih, 2005; Othman *et al.*, 2006; Li and Anderson, 2007) showed that cryogenic processing or low-temperature (LT) metallization results in an enhanced Schottky barrier height and reduced carrier trapping at the metal/semiconductor interface. Increasing the barrier height leads to low dark currents which are in turn critical for improving the minimum detectable power. Improving the metal/semiconductor interface leads to high speed

devices and improved detector sensitivity. However, this technique needs a special chamber with flowing liquid nitrogen during the cryogenic processing or metallization at room temperature, which consumed a lot of money. Meanwhile, dipping sample in liquid nitrogen (Lee *et al.*, 2005; Li and Anderson, 2005; and Othman *et al.*, 2006) also shown in an improved Schottky barrier height and leads to low dark currents of photodetector. Interestingly enough, Hashim *et al.*, 2004, have successfully reported that using ultra-cooling temperature treatment has essentially improved optical properties and surface quality of sample SiGe on p-silicon. Moreover, Hashim and Salih, 2005, have also reported the improvement of optical properties and surface quality of n-type Si (100) and p-type Si (100) using ultra-cooling temperature treatment.

Our initiative now is to apply the same method to improve the performance of Si based MSM photodetector. The surface roughness of the untreated and treated samples was obtained using AFM techniques. Optical properties of our samples were investigated using Raman spectroscopy and XRD machine operating at room temperature. Lastly, the Schottky barrier height and ideality factor have been calculated according to I-V characteristics of the devices.

## 2. Experimental procedures

Fresh monocrystalline n-type silicon (100) with a resistivity of 10-16 ohm-cm was used for the study. The Si was dipped in liquid nitrogen for 15 to 60 minutes at

atmospheric pressure. The sample was folded in Al foil to avoid direct contact with liquid nitrogen. This is followed by thermal evaporation of nickel (Ni) metal on the sample to form interdigitated Schottky contact electrodes. The structure of the MSM photodiodes consist of two interdigitated Schottky contact with finger width of 200  $\mu\text{m}$ , finger spacing of 400  $\mu\text{m}$ , and the length of each electrode was about 3300  $\mu\text{m}$ . It consists of four fingers at each electrode. After Ni metallization the MSM structure was subjected to annealing at 400°C for 10 minute in a conventional tube furnace in flowing nitrogen ambient. The electrical properties of the photodiodes were analyzed by means of I-V characteristics of the devices. Atomic force microscopy (AFM) was used to analyze the morphological properties of the samples. Optical properties of our samples were observed using Raman spectroscopy and XRD machine at room temperature.

### 3. Results and discussions

The Schottky contact properties of the MSM photodetector can closely described by the equation below (Rhoderick, 1998 and Rideout, 1975)

$$I = I_o \exp\left(\frac{eV}{nKT}\right) \left[1 - \exp\left(-\frac{eV}{kT}\right)\right] \quad (1)$$

Where  $I$  is the current,  $I_o$  is the saturation current.  $V$  is the bias voltage, and  $n$  is the ideality factor. The expression for the saturation current,  $I_o$  is

$$I_o = SA^*T^2 \exp(-q\Phi_B / kT) \quad (2)$$

Where  $S$  is the Schottky contact area,  $\Phi_B$  is the Schottky barrier height, and  $A^*$  is the Richardson with the value  $A^*$  of  $1.12 \times 10^{-6} \text{ Am}^{-2} \text{ K}^{-2}$  (for electron in n-type silicon) (Akkilic *et al.*, 2003). Equation (1.0) can be rewritten as

$$\frac{I \exp(eV/kT)}{\exp(eV/kT) - 1} = I_o \exp(eV/nkT) \quad (3)$$

At  $T \leq 370 \text{ K}$  and when  $V \leq -0.5 \text{ V}$ , equation (3.0) can be simplified to

$$I \exp\left(\frac{eV}{kT}\right) = I_o \exp\left(\frac{eV}{nkT}\right) \quad (4)$$

$$\ln I + \frac{eV}{kT} = \ln I_o + \frac{eV}{nkT} \quad (5)$$

Here, the plot of  $\left(\ln I + \frac{eV}{kT}\right)$  vs.  $V$  will give a straight line of the slope  $= e/nkT$  and y-intercept at  $\ln I_o$ .

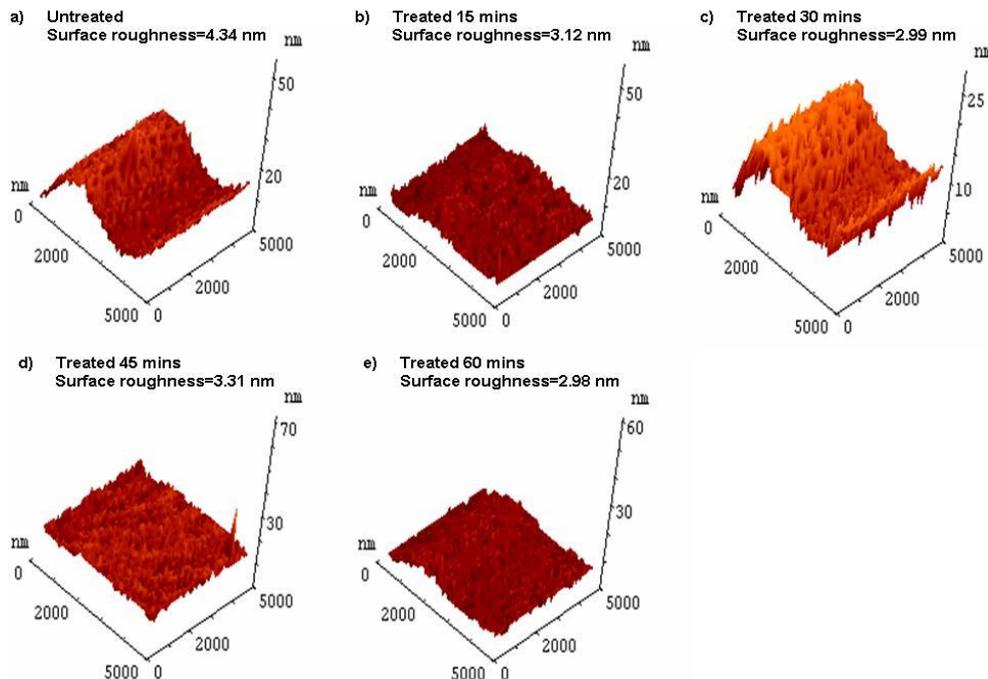


Fig. 1. AFM images from the surface of b) 15minute c) 30 minute d) 45 minute and e) 60 minute exposure time n type silicon (100) samples. Image from untreated sample a) is also included for comparison.

Fig. 1 shows AFM images of n type (100) silicon samples dipped for b) 15 minute c) 30 minute d) 45 minute and e) 60 minute in liquid nitrogen. Image from untreated sample a) is also included for comparison. In agreement

with the previous studies (Hashim *et al.*, 2004 and Hashim and Salih, 2005), surface roughness improves with increasing treatment time (untreated, surface roughness=4.34 nm)  $\rightarrow$  (15 minutes treatment, surface

roughness = 3.12 nm) → (60 minutes, surface roughness = 2.98 nm). After treatment, all the sample were deposited with Ni contact at room temperature followed by furnace anneal of 400°C, 10 minute in a conventional tube furnace in flowing nitrogen ambient.

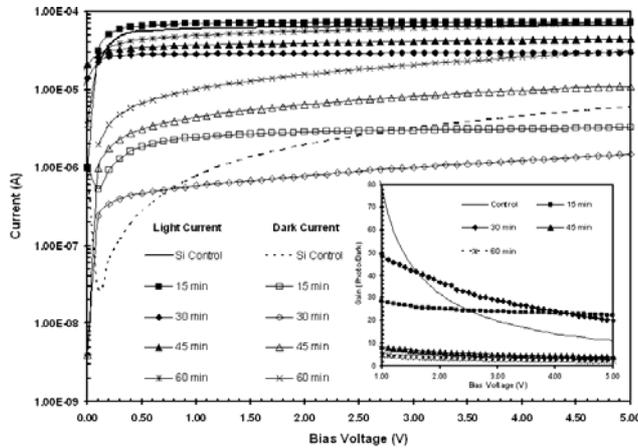


Fig. 2 Measured I-V characteristic of the n-type silicon (100) based MSM photodetector with cryogenic temperature treatment at various exposure times

Fig. 2 shows dark and photo I-V characteristics of n-type Si(100) based Ni MSM photodetector for all the samples. It can be seen that the exposure time changes both the dark and light current of MSM structure. More

specifically the treatment has decreased both dark and light currents of the MSM photodetector. In particular 30 minute treatment produced the lowest dark and light currents of all. However, 15 minute treatment produced the highest dark and light current. The 60 minute treatment produced the lowest current gain (inset) compared to other samples. Result from Figure 2 therefore suggest that the difference in I-V characteristics could be partly explained by the change in surface morphology particularly at Ni/Si interface, where smoother Ni/Si interface produce higher current than that of rougher interface. In addition to the I-V characteristics, the ratio of detector light current-to-dark current, i.e. Gain = light/dark is often quoted for performance evaluation as an optically control electronic switch. The inset of Figure 2 shows higher Gain compared to other exposure times.

Table 1 shows summary of the dark and photo current characteristics of the samples cooled at different exposure time. Generally, we found that cryogenic temperature treatment resulted in more significant changes to the dark and photo current characteristics compared to samples without combination treatment. Cryogenic treatment increased the barrier height as well as reduced the photo and dark current level, and also with a stable ideality factor when compared to the untreated sample. We suggest that this is mainly due to the better surface morphology of the combination treatment samples.

Figure 3 shows Schottky barrier height (SBH) of n-type Si(100) based Ni MSM photodetector for all the samples. It can be seen that the exposure time changes both the SBH for dark and light current of MSM structure.

Table 1 Summary of the dark and light current characteristic of the samples cooled at different exposure time.

Exposure Time (minute)	Ideality Factor, n	Barrier Height, $\Phi_B$ (eV)		Current at 5 V ( $\mu A$ )		Current Gain at 5 V (Photo/Dark)
		Dark	Photo	Dark	Photo	
Control	1.01	0.786	0.611	5.9751	66.692	11.162
15	1.00	0.708	0.603	3.2715	73.275	22.398
30	1.00	0.732	0.617	1.4795	29.696	20.072
45	1.00	0.693	0.612	44.783	11.013	0.246
60	1.00	0.675	0.612	72.804	31.205	0.429

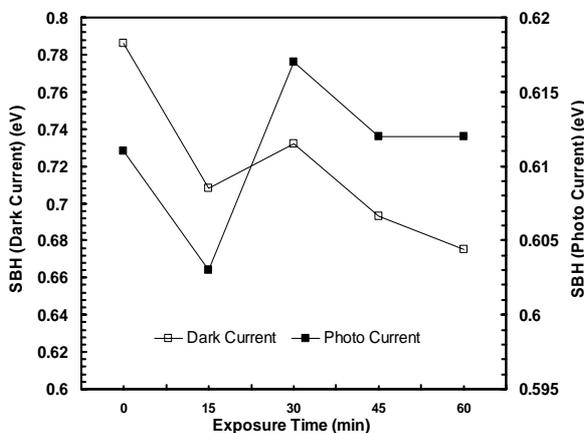


Fig. 3 Schottky barrier height (SBH) of dark and light current of n type Si (100) vs exposure time.

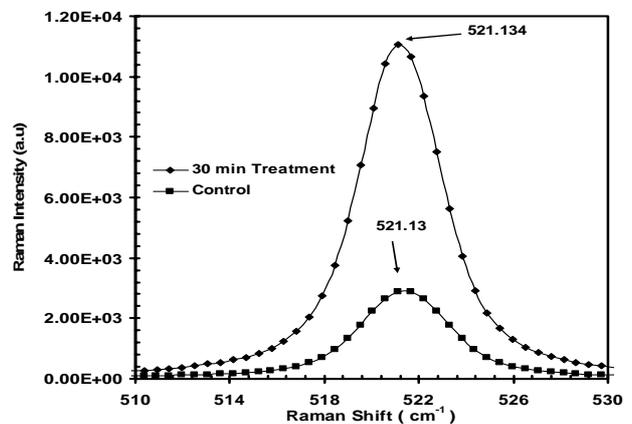


Fig. 4 Raman spectra of two samples; control and treated at 30 minutes treatment.

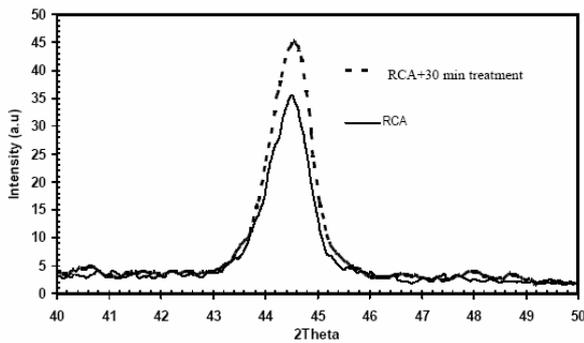


Fig. 5 XRD spectra of two samples; RCA and combination RCA+Cooling treatment.

Fig. 4 shows Raman spectra of temperature treated n-type silicon (100). The untreated Si also has been shown as a comparison. Obviously, there is no shift observable in the visible region. However, we found that the cryogenic temperature treatment has increased the intensity of Raman signal which can be related to better surface roughness suggested by Figure 1. Figure 5 shows XRD spectra of temperature treated n-type silicon (100). We found that the cryogenic temperature treatment has also increased the intensity of XRD inconsistency with Raman result.

#### 4. Conclusions

We have shown the cheaper and easier method to modify dark and photo current of monocrystalline n-type silicon (100) Ni MSM photodetector using cryogenic temperature treatment. The modified current is associated with the change of Ni/Si interface roughness. Smoother Ni/Si surface produces high SBH values for dark current and also high SBH values for light currents. The treatment also increased the intensities of Raman spectroscopy and XRD peak at room temperature.

#### Acknowledgements

The authors wish to thank School of Physics for technical assistance. Support from IRPA RMK-8 Strategic and Universiti Sains Malaysia is gratefully acknowledged.

#### References

- [1] Chui, C. O., Okyay, A. K., Sarawat, K. C. IEEE Photonic Tech Lett. **15**, 11, 158-1587. (2003),
- [2] Laih, L. H., Wang, J. C., Chen, Y. A., Tsay, W. C., Jen, T. S., Chen, J. S., Hong, J. W. Jpn. J. Appl. Phys. **36**, Pt.1, no.3B. (1997),
- [3] Sharma, A.K., Scott, K.A.M., Brucek, S.R.J., Zolper, J.C. and Myers, D.R., IEEE Photonics Tech. Lett. **6**, 635. (1994),

- [4] Liu, M.Y., Chou, S.Y., Alexandrou, S., Wang, C.C. and Hsiang, T.Y. IEEE Trans. Electron Devices **40**, 2145. (1995),
- [5] Shi, Z.Q., Wallace, R.L., and Anderson, W.A. Appl. Phys. Lett., **59**, 446 (1991).
- [6] Shi, Z.Q., Wallace, L.R., and Anderson, W.A. 1992, Cryogenic Processing Of Metal/InP/Schottky Contacts. Proc. of the Indium Phosphide and Related Material, 1992, Fourth International Conference on 21-24 April 1992, p.332-335.
- [7] Lee, H. J., Anderson, W. A., Hardtdegen, H., L<sup>□</sup>th, H. Appl. Phys. Lett. **63**(14), 1939 (1993).
- [8] He, L., Shi, Z.Q., and Anderson, W.A. (1994), Interface Analysis For Cryogenic Processed Metal/InP. Proc. of the Indium Phosphide and Related Materials, Sixth International Conference, p.26-209.
- [9] Wang, A. Z. H., Anderson, W. A., and Haase, M. A. J. Appl. Phys. **77**, 3513 (1995).
- [10] Clark, S. A., Wilks, S. P., Kestle, A., Westwood, D. I. and Elliot, M. Appl. Surf. Sci. **352-354**, 850 (1996).
- [11] Palmer, J. W., Anderson, W. A., Hoelzer, D. T., Thomas, M. J. Electron. Mat., **25**, 1645 (1996),
- [12] He, L. Solid-State Electron. **41**, 1881 (1997).
- [13] Cammack, D. S., McGregor, S. M., McChesney, J. J., Clark, S. A., Dustan, P. R., Burgess, S. R., Wilks, S. P., Peiro, F., Ferrer, J.-C., Cornet, A., Morante, J. R., Kestle, Westwood, A., D. I., Elliot, M. Appl. Surf. Sci. **123/124**, 501 (1998).
- [14] Hong, H. and Anderson, W. A. IEEE Transactions on Electron Devices, **46**, 6 (1999).
- [15] He, L., Siewenie, J. E. Surface and Coating Tech. **150**, 76 (2002),
- [16] Hashim, M. R., Salih, Kifah. Q., Bagnell, D. Lamraksa, P., Electrochem. Soc. Proc, 299 (2004),
- [17] Lee, Y. C., Hassan, Z., Abdullah, M. J., Hashim, M. R., Ibrahim, K. Microelectronic Eng., **81**, p.262-268. (2005).
- [18] Li, M., Anderson, W.A. Material Research Society Symposium Proc.. **864**, 313 (2005),
- [19] Hashim, M. R., Salih, Kifah Q. Microelectronic Eng. **81**, 243 (2005),
- [20] Othman, S., Yam, F. K., Abu Hassan, H. and Hassan, Z. Material Science Forum, **517**, 281 (2006),
- [21] Li, M., and Anderson, W.A. Solid-State Electronic. **51(1)**, 72 (2007).
- [22] Rhoderick, E. H., Williams, R.H., Metal-semiconductor Contacts, Second ed., (Oxford University Press, New York, 1998) p. 39.
- [23] Rideout, V.L. Solid-State Electron. **18**, 541. (1975),
- [24] Akkiliç, K., Kilicoglu, T., Turut, A. Physica B **337**, 388 (2003).

\*Corresponding author: mzmy83@gmail.com