Vol 17 No 10, October 2008
1674-1056/2008/17(10)/3644-05

Chinese Physics B

© 2008 Chin. Phys. Soc.
and IOP Publishing Ltd

A CVD diamond film detector for pulsed proton detection*

Wang Lan(王 兰)[a)†], Ouyang Xiao-Ping(欧阳晓平)[a)b)d)], Fan Ru-Yu(范如玉)[a)b)],
Jin Yong-Jie(金永杰)[a)], Zhang Zhong-Bing(张忠兵)[b)], Pan Hong-Bo(潘洪波)[b)],
Liu Lin-Yue(刘林月)[b)], Lü Fan-Xiu(吕反修)[c)], and Bu Ren-An(卜忍安)[d)]

[a)] *Department of Engineering Physics, Tsinghua University, Beijing* 100084, *China*
[b)] *Northwest Institute of Nuclear Technology, Xi'an* 710024, *China*
[c)] *Material College, Beijing University of Science and Technology, Beijing* 100083, *China*
[d)] *Xi'an Jiaotong University, Xi'an* 710049, *China*

(Received 15 August 2007; revised manuscript received 27 May 2008)

A chemical vapour deposition (CVD) diamond film detector was prepared and the main characteristics for pulsed proton detection were studied at Beijing Tandem Accelerator. The result shows that the charge collection efficiency of the detector increases with increasing electric field intensity and reaches to 9.44% at 5 V/μm with the charge collection distance of 15.9 μm. The relationship between the sensitivity of the detector and proton energy is consistent with the Monte Carlo (MC) simulation result. Its plasma time for a pulse with 4.85×10^5 protons is 11.2ns. The dose threshold for onset of damage under 9MeV proton irradiation in the detector is about $10^{13}\,\mathrm{cm}^{-2}$. All of the results show that a CVD diamond detector has fast time response and high radiation hardness, and can be used in pulsed proton detection.

Keywords: pulsed proton detection, CVD diamond film, semiconductor detector
PACC: 2940P

1. Introduction

Compared with semiconductor detectors like the Si-PIN, the high band gap (5.5 eV) and fast carrier velocity of diamond make it an ideal material for radiation detector.[1] Detectors made of CVD diamond films have been paid more and more attention since the 1990s when the CVD technique was gradually becoming mature.

CVD diamond detectors were mostly used for single particles or γ-rays detection in the past few decades[2−4] while few researches were done for its application in pulsed particle detection. However, in the recoil-proton neutron detection system,[5] the most important work is to choose a proper detector for pulsed proton detection. The radiation damage and the slow time response are the main factors which limit the use of semiconductor detectors for pulsed charged particle detection. A diamond detector with low noise, fast time response, small plasma time and high radiation hardness is a good alternative.

In this paper, a CVD diamond film detector is prepared and the characteristics for pulsed proton detection including the sensitivity versus proton energy, the charge collection efficiency, the time response and the radiation hardness are studied and discussed.

2. Detector preparation and experiments

The CVD diamond film was chemically cleaned and tested before the preparation of the detector. The spectra of Raman and the x-ray diffraction pattern are shown in Figs.1 and 2 respectively, the sharp peak at

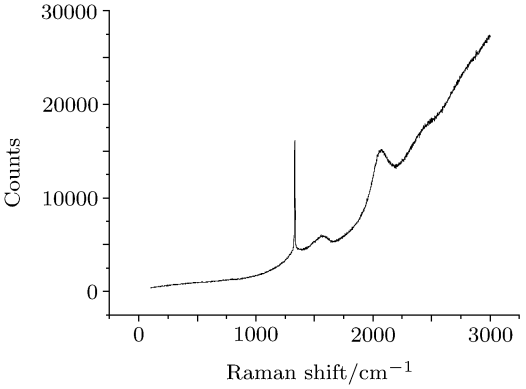


Fig.1. Raman spectrum of the CVD diamond film.

*Project supported by the National Natural Science Foundation of China (Grant No 10675074).
†E-mail: wanglan_99@hotmail.com

at 1332 cm^{-1} in the Raman spectrum and the three characteristic peaks in the XRD pattern indicate the material is diamond. In the Raman spectrum the envelope peaks are the indication of the presence of a little non-diamond carbon and other defects in the film.

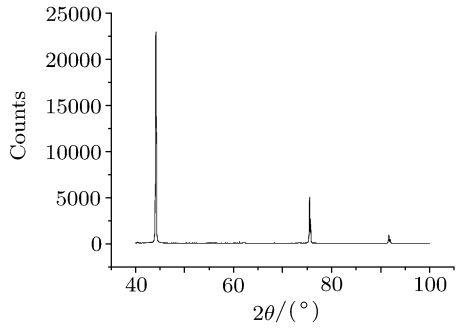


Fig.2. XRD pattern of the CVD diamond film.

The photo of the CVD diamond detector is shown in Fig.3. In the detector the film was capsulated in the metal-semiconductor-metal structure like sandwich. Contacts were formed on both sides of the film by thermal evaporation of Ti–Pt–Au metal. Two printed circuit boards (PCB) were used to clamp the film. On each side, the Au metal was connected to the alignments on the PCB by four Au wires so that electric signal could be transferred to the outside circuit.

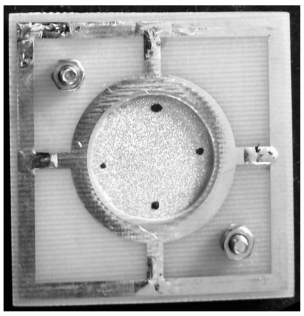


Fig.3. Photo of the CVD diamond film detector.

The sensitive thickness (the distance between the two electrodes) of the detector is 160 μm, and the total thickness of the metal is as thin as 20 nm so that the energy deposited in metal by MeV protons can be ignored.

Dark current versus the electric field intensity was tested in darkroom and the result is shown in Fig.4. When the electric field intensity is less than ± 5 V/μm, the dark current of the detector is less than ± 10 nA and the curve is linear and symmetric. This means that the film is capsulated clean enough and the contacts are both ohmic. Calculated according to the V-A theorem, the intrinsic resistivity of the diamond film in the detector is as high as 10^{13} Ωcm.

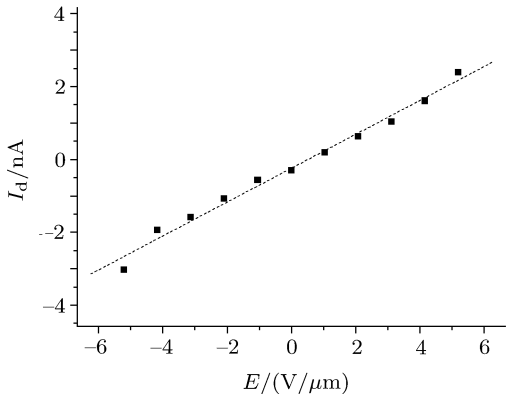


Fig.4. The dark current vs. electric field intensity curve of the detector.

The test was performed at Beijing Tandem Accelerator HI-13 which could supply proton beams in both continuous and pulsed modes. The sketch of the experiments is shown in Fig.5. The beam channel is connected with the vacuum chamber in which the CVD diamond detector (Dia Det) and a Faraday Canister (F.C.) detector are installed. The CVD diamond detector is installed on the bottom of the chamber which could be turned around the axes. The F.C. detector is directly fixed to the beam channel on the inner top of the chamber and is used for detecting the beam intensity as a standard detector. The signal current of the F.C. detector is equal to the current of proton beams.

The sensitivity of the detector was tested under 4–14 MeV current proton beams with the sensitivity of a detector to particles defined as the charge generated by the circuit per incident particle. The signal current (I_s) and proton current (I_p) were read from the current meters A and B respectively. So the sensitivity of the detector (S) can be calculated by $S = A_{eff} I_s/(I_p/e)$, where e is the electron charge (1.6×10^{-19}C) and A_{eff} is the area of the sensitive region which can response to particles. Changing the proton energy, the sensitivity versus proton energy curves under a certain electric field can be recorded. Then, changing the electric field, the curves of sensitivity versus proton energy under different electric field can be made.

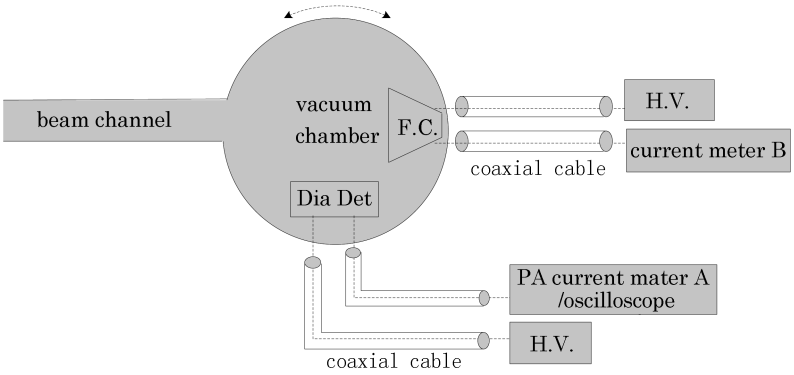


Fig.5. The sketch of the experiments.

Aimed at pulsed detecting, the time response of the detector was tested with pulsed proton beams and a femtosecond UV laser separately. The proton beams were generated by segmenting a 310 nA proton beam at the frequency of 4 MHz (4.84×10^5 protons in a pulse) and were only 1.5ns wide. The response of the detector to UV laser was carried out in the Northwest Institute of Nuclear Technology.

Finally, the curve of signal current decrease with irradiation dose was investigated under a continuous 13 nA 9 MeV proton beam. So the dose threshold for the onset of damage in the detector was obtained. The intensity of the proton beam was read before and after the irradiation. Then the irradiation dose was calculated through multiplying the proton beam intensity by the irradiation time.

3. Results and discussion

3.1. Sensitivity versus proton energy

The sensitivity curve of the detector versus proton energy at an electric field 5 V/μm is shown in Fig.6. The range of a 6 MeV proton is about 158 μm, which is almost the same as the distance between the two electrodes of the detector used in the experiment. So the sensitivity increases linearly with the proton energy up to 6 MeV, and then decreases. The sensitivity of the detector to 14 MeV proton beams is 6.0×10^{-15} C·cm^2/proton. The uncertainty of the results is larger when the proton energy is less than 6 MeV because it is hard to tune the accelerator to a very good state for those energies.

The theoretic curve of the detector sensitivities versus proton energy (dashed line in Fig.6) is calculated by multiplying the Monte-Carlo sensitivity results by the charge collection efficiency of 9.44% which will be discussed below. It is in accord with the experimental result.

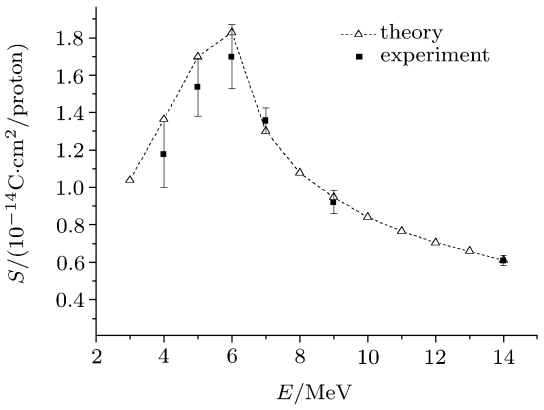


Fig.6. Sensitivity curve of the detector vs. proton energy (E=5 V/μm).

3.2. Charge collection efficiency

Traps composed of impurities and crystal boundaries in the film may reduce the charge collection efficiency. If an electron or a hole excited by the incident protons is trapped and not released in a relatively long period, the signal caused by it will be over. So the charge collection efficiency (η), defined as the ratio of the charge collected by the detector to that generated by the incident radiation, is the basic parameter of a CVD diamond detector.

The relationship between charge collection efficiency (η) and charge collection distance (σ) is deduced by Hecht:[6]

$$\eta = (\sigma/L)[1-(\sigma/4G)(1-\exp(-2G/\sigma)) \times (1+\exp(2(G-L)/\sigma))], \quad (1)$$

where G is the range of the incident radiation, and L is the distance between the two electrodes. From this relationship, η increases linearly with increasing σ until σ reaches to $5\,G$ ($150\,\mu$m). Since σ increases linearly with the electric field intensity,[7,8] η also increases linearly with increasing electric field.

The sensitivity is mainly determined by two factors: the deposited energy of the incident radiation and the charge collection efficiency. In the Monte-Carlo simulation software 'srim 2003',[9] only the deposited energy of the incident particles can be calculated and the trapping effect will not be considered. So the charge collection efficiency can be obtained by comparing the sensitivity from the experiment with the one 'srim 2003'.

The charge collection efficiency versus the electric field intensity of the detector is shown in Fig.7. It increases almost linearly with increasing electric field intensity and reaches to 9.44% at $5\,\mathrm{V}/\mu$m. Calculated based on Hecht's theory, the charge collection distance reaches to $15.9\,\mu$m at $5\,\mathrm{V}/\mu$m. The uncertainty comes mainly from the accelerator, which is less than 5%.

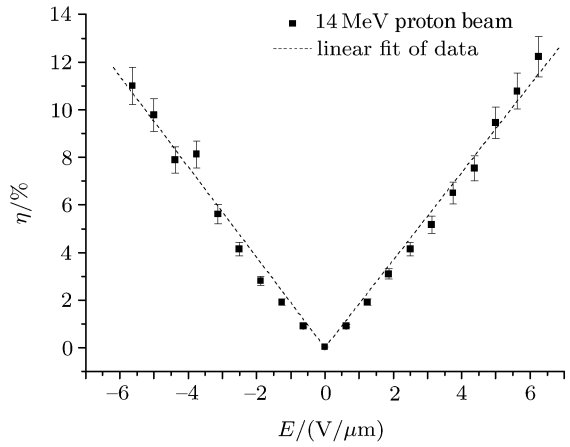


Fig.7. Charge collection efficiency of the detector (for 14 MeV proton beam).

response of the detector. Seibt *et al* deduced the formula of the plasma time for semiconductor detectors in 1973.[10] The plasma time of diamond is shorter than other semiconductor detectors, for the dielectric constant and diffusion constant of diamond are larger than other semiconductors ($90\,\mathrm{cm}^2/\mathrm{s}$ for diamond[11] and $16\,\mathrm{cm}^2/\mathrm{s}$ for Si[12]).

Response waveforms of the detector to both the pulsed proton beam and the femtosecond UV laser are shown in Fig.8. The rise time and the FWHM of the former are 6.0 ns and 13.3 ns, and those of the latter are 3.8 ns and 7.1 ns respectively. Obviously, the time response wave is extended by the plasma effect. The whole response process is composed of two subprocesses: the dispersing process and the no-plasma response of the detector. The dispersing process can be considered as the incident pulse with t_p, and the no-plasma response can be considered as the transforming system which is the same as the response under the femtosecond UV laser. Taking the UV response waveform as the transfer function of the detector system, the plasma time of 11.2 ns can be acquired through deconvolution.

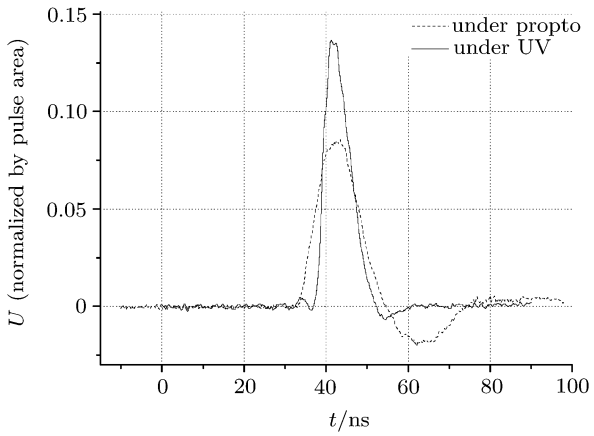


Fig.8. Time response waveforms of the detector.

3.3. Time response (plasma time)

Different from electromagnetic radiation，plasma clusters is generated along the track of the protons because the energy loss of the charged particle is very large. Then the clusters may be gradually dispersed by the electric field intensity on the detector. The dispersing time is called plasma time (t_p), and the plasma time of a semiconductor detector is usually in nanosecond and affected by the type, the energy and intensity of the incident particles. It may slow down the time

3.4. Radiation hardness

The C atoms may be moved from the lattice by the energy deposited from the incident protons and traps are produced. As a result, the charge collection efficiency decreases and so does the signal current. The radiation damage curve of the detector is shown in Fig.9. We can see the signal decreases with increasing irradiation dose. The reduction is less than 3.5% when the dose is less than $10^{13}\,\mathrm{cm}^{-2}$, and is about 15% when the dose reaches $10^{14}\,\mathrm{cm}^{-2}$. The dose threshold

for the onset of damage in the CVD diamond film detector is 3 orders of magnitude higher than that in Si-PIN detectors.[13] The dark current does not change obviously after the proton irradiation.

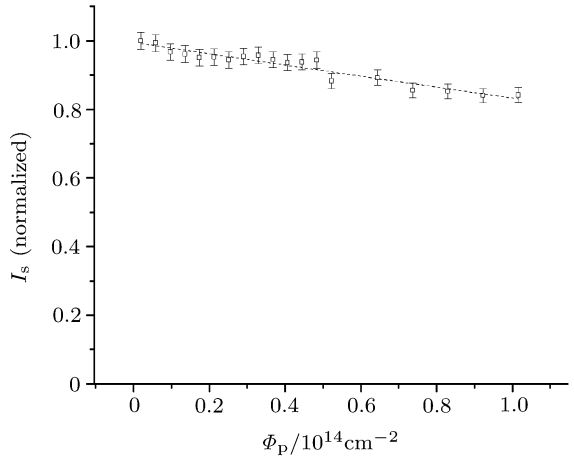


Fig.9. Signal current curve (normalized) of the detector under 9MeV proton irradiation.

4. Conclusions

A CVD diamond film detector has been made and tested. The results are as follows: a) The dark current is less than 2 nA with an intrinsic resistivity of $10^{13}\,\Omega$cm which is so large that no PN junctions are needed. b) The charge collection efficiency is about 9.44%; the charge collection distance is 15.9μm; and the relationship between the sensitivity of the detector and proton energy is consistent with the simulation result. c) The FWHM of the response waveform to a pulsed proton beam of 4.84×10^5 protons is 13.3 ns with the plasma time of 11.2ns. d) The dose threshold for the onset of damage under 9MeV proton irradiation in the detector is about $10^{13}\,cm^{-2}$, which is 3 orders of magnitude higher than that in Si-PIN detectors. From the results and discussion above, we can conclude that CVD diamond film detector is an ideal semiconductor detector for pulsed proton detection.

Acknowledgments

We thank Professor Haihong Xia and his team at China Institute of Atomic Energy for their great help so that the work was successfully finished on the Beijing Tandem Accelerator. Liu Demin and Zhang Yongsheng at Northwest Institute of Nuclear Technology also gave us great help during the study.

References

[1] Kashiwagi T, Hibino K, Kitamura H, Kunishiro M, Okuno S, Takashima T, Uchihori Y, Yajima K, Yokota M and Yoshida K 2006 *IEEE Transactions on Nuclear Science* **53** 630

[2] Bergonzo P, Brambilla E A and Tromson D 2002 *Nuclear Instruments and Methods in Physics Research* A **476** 694

[3] Mainwood A 1998 *Diamond and Related Materials* **7** 504

[4] Ouyang X P, Wang L, Fan R Y, Zhang Z B, Wang W, Lü F X, Tang W Z and Chen G C 2006 *Acta Phys. Sin.* **55** 2170 (in Chinese)

[5] Ji C S 1998 *Neutron Detection Experiment Method* (Beijing: Atomic Energy Press) p193

[6] Hecht K 1932 *Z. Phys.* **77** 235

[7] Marinelli M, Milani E, Paoletti A, Tucciarone A, Rinati V, Angelone M and Pillon M 1999 *Appl. Phys. Lett.* **75** 3216

[8] Liu E K, Zhu B S and Luo J S 2005 *Semiconductor Physics* (Beijing: Publishing House of Electronics Industry) p108 (in Chinese)

[9] Ziegler J F 2004 *Nuclear Instruments and Methods in Physics Research* B **219/220** 1027

[10] Seibt W, Sundstrom K E and Tove P A 1973 *Nuclear Instruments and Methods* **113** 320

[11] Pan L S and Kania D R 1993 *Diamond: Electronic Properties and Applications* (London: Kluwer) p253

[12] Koike J, Parkin D M and Mitchell T E 1992 *Appl. Phys. Lett.* **60** 1450

[13] Robert W K 1971 *Semiconductor Detectors for Use in the Current Mode* UCRL51011 p53