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Effect of swift heavy Kr ions on complex permittivity of silicon PIN diode

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ABSTRACT

The complex permittivity has been researched on silicon PIN diodes irradiated by 2150 MeV heavy Kr ions in this article. The difference of complex permittivity spectra from 1 to 10^7 Hz between irradiated and unirradiated were observed and discussed. The current-voltage (I-V) and capacitance-voltage (C-V) characteristics were measured at room temperature (300 K) to study the change of electrical properties in diode after irradiation. Deep level transient spectroscopy (DLTS) was used to investigate damages caused by 2150 MeV heavy Kr ions in diode. Two extra electron traps were observed, which were located at E_C-0.31 eV and E_C-0.17 eV. It indicated that new defects have been formed in PIN diode during irradiation. A comparison of the results illustrated that not only the carrier density but also the recombination of electron-hole pair have important influences on the properties of complex permittivity. These results offer a further indication of the mechanism about the complex permittivity property of semiconductor device, which could help to make the applications for the semiconductor device controlled by electric signals come true in the fields of optoelectronic integrated circuits, plasma antenna and so on.

1. Introduction

With the development of photoelectric device and photoelectric integrated circuit, as an important parameter of the Maxwell's equations, the dielectric constant has attracted interests. It is well known that swift heavy ion irradiation can change some electrical properties of semiconductor devices [1]. But the influence on dielectric constant of semiconductor by irradiation has not been carefully investigated.

It has been confirmed that complex permittivity of PIN diode could be modulated by direct current bias (DC bias) due to the carriers density changed in the intrinsic layer (I-layer), for the neutral plasma would be built up in the I-layer if the concentrations of carriers were enough high [2]. Irradiation was used as a powerful tool to investigate the properties of the semiconductor materials and devices [3]. The heavy ions could create displacement damage in semiconductor devices, which changes the carrier life-time, carrier concentration and other electrical properties [4]. However, does irradiation affect the complex permittivity of semiconductor devices? The aim of this work is to study the complex permittivity of PIN diode affected by swift heavy ion irradiation.

2. Experiment

The PIN diodes were made of wafers of n-type silicon single crystal having a resistivity of 10^4 Ω·cm as shown in the previous work [2]. Both sides of wafers were polished and the final thickness was 0.15 mm. The P^+-layer and N^+-layer were created by 10^{19} cm^{-3} boron and 10^{20} cm^{-3} phosphorous diffusion, respectively. The thickness of either P^+-layer or the N^+-layer were about 0.01 mm. And the thickness of I-layer was 0.13 mm. Finally, wafers were subdivided of a size of 0.15 mm by 1 mm by 1 mm, having Au contacts.

Heavy ions irradiation experiment was performed at the Heavy Ion Research Facility in Lanzhou (HIRFL) at the Institute of Modern Physics, Chinese Academy of Sciences, with 2150 MeV $^{86}Kr^{26+}$ ion beam. The ion beam fluence is 1×10^9 ions/cm^2. The dielectric properties of all samples were measured by broad band dielectric spectrometer of Novocontrol Technologies GmbH & Co. KG over the combined electromagnetic wave frequency range of 1–10^7 Hz.

When semiconductors are irradiated, the induced changes to the physical properties can be measured by the results of current-voltage (I-V) and capacitance-voltage (C-V) measurements of diodes. The changes of physical properties are reflected on the electrical properties which are caused by changing the concentration of free charge carriers [5]. The samples were characterized at

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300 K with I-V and C-V measurements, performed by Agilent B1500A Semiconductor Device Analyzer.

In order to know what defects were induced into the sample, the DLTS spectra were scanned at temperatures from 78 K to 330 K, with different lock-in frequencies: 180, 480, 780, 1080 and 1380 Hz. All samples were measured for the same reverse bias voltage (U_R) of −6 V, filling-pulse height (U_P) of 0 V and filling-pulse width of 30 μs.

The uniformity of Si PIN diodes was checked by first measuring 80 devices before irradiation. No significant difference in the behavior of these samples was observed. So it is reasonable to take one of these typical curves as the behavior before irradiation. The same methodology was applied to the irradiated samples. There were 60 devices were irradiated by 2150 MeV $^{86}Kr^{26+}$ ion beam with the same fluence of 1×10^9 ions/cm^2.

3. Results and discussion

According to our previous research, the complex permittivity of PIN diode could be modulated by DC bias due to the carriers density changed in the intrinsic layer [2]. Actually, the changes of carrier density in PIN diodes were controlled by DC current density which was determined by DC bias. To ensure the current density were the same in unirradiated and irradiated diodes, 100 mA of direct current was loaded on all devices during complex permittivity measurement in this research. The complex permittivity results of irradiated PIN diode and unirradiated PIN diode are given in Fig. 1(a) and (b), including the dielectric constant (ε′, real part of complex permittivity) and the dielectric loss (ε″, imaginary part of complex permittivity). It could be clearly seen that the dielectric response of real permittivity in unirradiated diode was much stronger than that in irradiated diode. The negative permittivity occurred in unirradiated diode, while it could not be found in irradiated diode in the frequency range of from 10^5–10^7 Hz. The ε″ of two diodes were much the same. According to the previous study [2], ε′ was affected by the carrier density. However, the results above indicated that there were some other critical influences on ε′. After radiation, the defects, which have one or more levels in the band gap, were created in semiconductor materials. Then electron–hole pairs generated and recombined constantly, the carriers were trapped by defects, donors and acceptors were compensated and other electrical degradation effects [6]. All of those would affect important parameters: the free carrier mobility and density, resistivity, generation and recombination of carrier and so on.

To make the cause of the changes clearly, I-V characteristics of irradiated and unirradiated PIN diodes measured at 300 K. The typical I-V results were shown in Fig. 2, which reveal that the PIN diode can work normally after irradiation. A slight increase of current under the forward bias was observed as a result of radiation as shown in Fig. 2. As the reverse bias increased, an increase in leakage current was observed in two samples. However, the leakage current was several times larger in irradiated than that in unirradiated diode, which means the carrier lifetime decayed after irradiation [7]. During heavy ions irradiations, displacement damage was generated in the silicon bulk of PIN diode. Displacement damage can increase the number of defects in the silicon bulk, resulting in decreasing the lifetime of the minority-carriers. Consequently, the reverse current was increased.

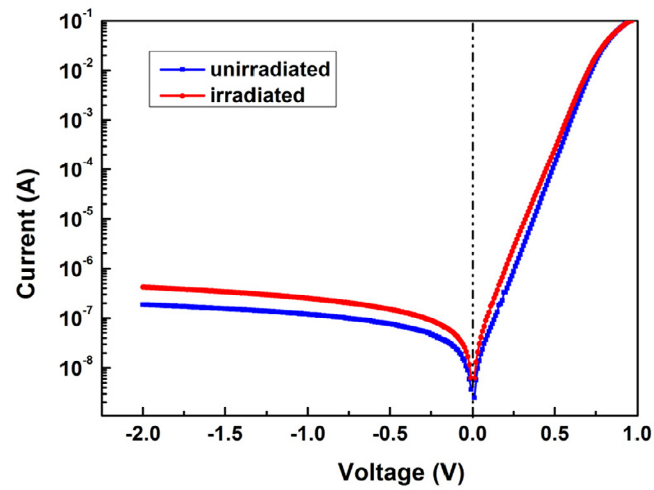

Fig. 2. I-V characteristics of PIN diodes at 300 K.

Fig. 3(a) shows the plot of $1/C^3$ (F^{-3}) as a function of voltage (V) measured at 1 MHz frequency at 300 K. The capacitance increased with decreasing reverse voltage for both. But the capacitance of irradiated diode was lower than that of unirradiated. Because electron traps were introduced into the sample during the irradiation process [8]. The change of free carrier concentration (ΔN_D) between irradiated and unirradiated samples was determined from the slope of the plots. C-V data were used to extract the concentration using the standard equations (1) and (2):

$$N_D = \frac{C^3}{qA^2\varepsilon_0\varepsilon_S}\left(\frac{dC}{dV}\right)^{-1} \quad (1)$$

$$W = \frac{A\varepsilon_0\varepsilon_s}{C} \quad (2)$$

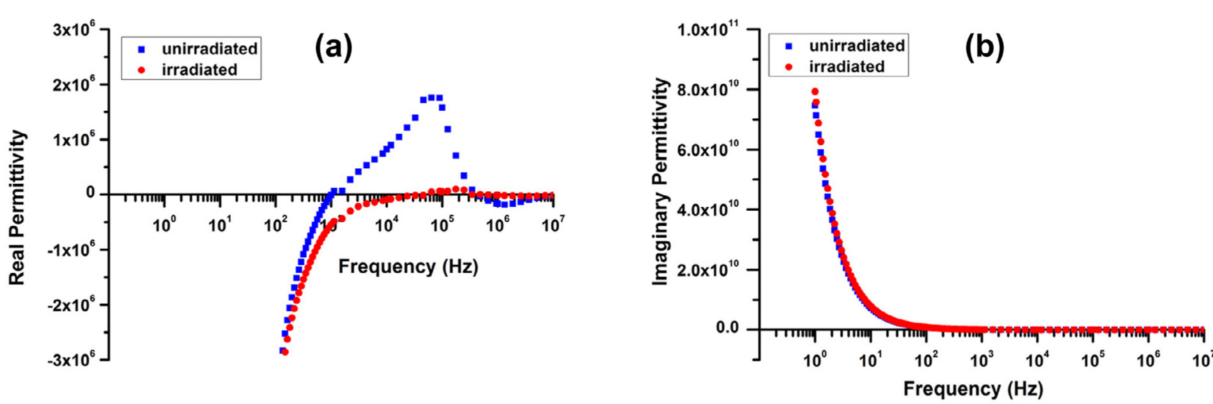

Fig. 1. (a) The real part of complex permittivity under direct current of 100 mA; (b) The imaginary part of complex permittivity under direct current of 100 mA.