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Novel phenomenon of negative permittivity in silicon-based PiN diodes induced by electron irradiation

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ABSTRACT

The negative permittivity of silicon-based PiN diodes is investigated experimentally in the frequency range from 1 Hz to 10 MHz, where electron irradiations and annealing thermal treatments are carried out. The permittivity is found be greatly affected by electron irradiations. In addition, the dispersion-free region is found be occurred in the samples irradiated by electron dose≥5.4646 × 10^{14} e/cm^2. Besides, annealing treatments also have an effect on the permittivity. It is interesting to find that, the annealing treatments lead to more negative platform (i.e., dispersion-free region) values of permittivity for samples irradiated by electron dose≥5.4646 × 10^{14} e/cm^2, and the negative platform values under 350 °C annealing treatment are lower than that under 150 °C annealing treatment when the electron irradiation dose is higher than 1.0929 × 10^{15} e/cm^2. The novel phenomenon found in this work may provide new ideas for the application of semiconductor devices in information transmission, storage and processing.

1. Introduction

Negative permittivity is a key parameter for the metamaterials, which is called as left-hand materials with negative permittivity (ε'<0) and negative permeability (μ'<0) simultaneously. In recent years, metamaterials have attracted more and more attentions due to its special electromagnetic properties and potential for some novel applications [1–4]. It is well known that the property of negative permittivity of metamaterials is mainly obtained from their special designed artificial periodic structure, including split ring resonator [5,6], multi-layer structures [7], twisted structure [8], cut-wire pairs [9], etc. However, it is difficult and also expensive to realize those precisely designed structures under common conditions. Besides, some researches on negative permittivity of composites have been reported [10,11]. However, research on negative permittivity obtained by semiconductor devices has rarely been reported. The negative index of materials can be realized when the permittivity is negative. Hence, the negative permittivity becomes the primary indicator to build new metamaterials naturally. Therefore, it is worth and important to study how to realize the negative permittivity for materials.

In our previous work [12], we have studied complex permittivity of PiN diodes under DC bias. At the on-state (with forward bias over 0.7 V), the negative permittivity phenomenon is observed in the frequency range of about 10^5–10^7 Hz. However, at the off-state

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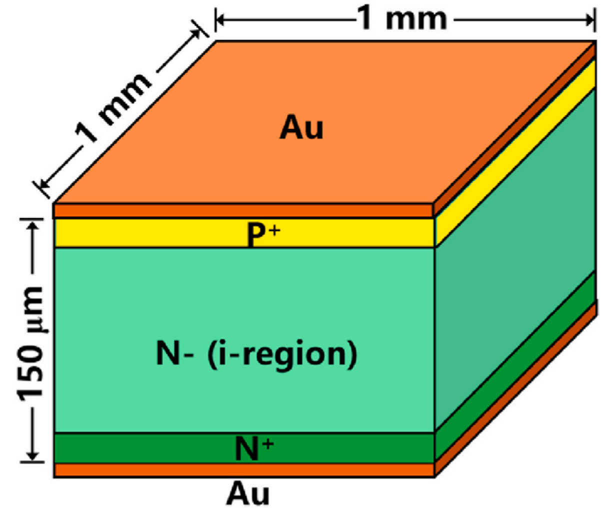

Fig. 1. Schematic diagram of the PiN diode for study.

Table 1
Sample numbers and irradiation doses.

Number	0#	1#	2#	3#	4#
irradiation dose ($\times 10^{14}$ e/cm^2)	0	1.0929	5.4646	10.929	54.646

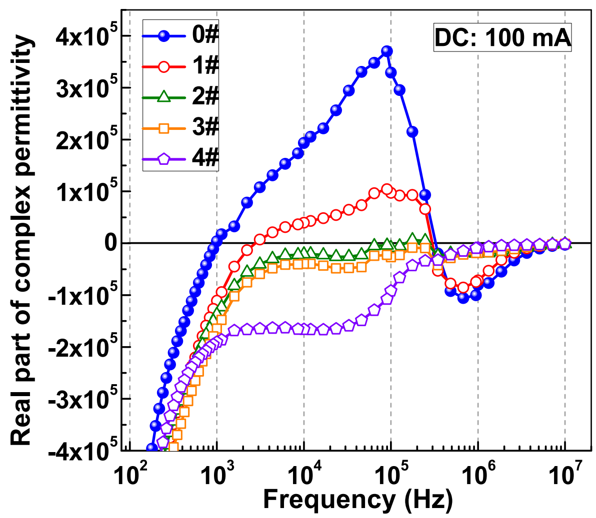

Fig. 2. Frequency dependence of permittivity of samples.

(with forward bias below 0.7 V), the negative permittivity phenomenon disappears at the frequency range of about 10^5–10^7 Hz. Besides, the negative permittivity phenomenon of the PiN diodes can be enhanced and its corresponding frequency range is enlarged as the forward bias voltage increases, which reveals the controllable negative permittivity by the voltage bias.

In this paper, we further study the effect of electron irradiation on the negative permittivity phenomenon of the PiN diodes. The main aim of this paper is to report some interesting phenomena of negative permittivity in PiN diodes after electron irradiation and annealing treatments. This work finds that PiN diodes can obtain negative permittivity without special designed artificial structures, complex fabrication or high cost. Moreover, the negative permittivity in PiN diodes can not only be modulated by electrical bias but also be modulated by electron irradiation dose and annealing process, which make it possible to develop new types of electromagnetic wave transport and modulator devices. In addition, PiN diodes can be integrated with other types of semiconductor devices by the same process flows, which may have important significance for potential applications in the field of waveguide, filter, transmitter, detector, antenna, etc.

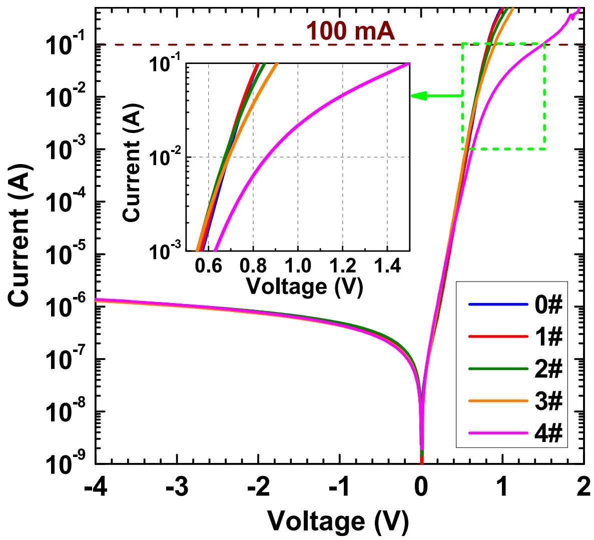

Fig. 3. I–V characteristics of PiN diode samples.

2. Experiment

In this work, silicon PiN diodes have been selected due to its simple structure, relatively stable property and mature fabrication process. More importantly, when the diode is forward biased and turned on, electrons and holes inject from the heavily doped regions into the lightly doped i-layer region, and the concentrations of electrons and holes are approximately the same. Then, the neutral plasma is built up and the dielectric response can be generated as presented in our previous research [12]. Fig. 1 shows the schematic diagram of the PiN diode for study, which is fabricated by using n-type silicon single crystal wafers with a resistivity of 10^4 Ω cm (the doping concentration is about 10^{13} cm^{-3}). The P^+-layer and N^+-layer are formed by 10^{19} cm^{-3} boron and 10^{20} cm^{-3} phosphorous diffusion, respectively. The thickness of i-region (N-region) is about 130 μm, and the thicknesses of the P^+-layer and N^+-layer are both about 10 μm. Finally, wafers are plated by Au on the both sides, and then are subdivided with a size of 1 mm × 1 mm.

All the samples are irradiated vertically from P^+-layer with 1.7 MeV electron irradiation energy by scanning irradiation method. The electron beam current is 3.5 mA and the scanning speed is 2.63 m/min. Table 1 shows numbers of irradiated samples and the electron irradiation doses. The permittivity values are tested by the broad band dielectric spectrometer of Novocontrol Technologies GmbH & Co. KG. All samples was loaded 100 mA of DC (direct current) at room temperature. And the frequency range is 1 Hz–10 MHz.

3. Results and discussion

From studies on electron irradiation effect on the PiN diodes, an interesting phenomenon is found. Fig. 2 shows frequency dependence of permittivity of PiN diodes samples, where all samples are loaded DC bias current of 100 mA in order to ensure the dielectric response. As shown in Fig. 2, as the irradiation dose increases, the original positive value of permittivity gradually becomes negative in the frequency range of about 10^3–10^5 Hz. In addition, a negative value platform of permittivity occurs over a range of frequencies with the increase of irradiation dose. That means the permittivity is nearly constant in the frequency range with the negative value platform of permittivity, namely, dispersion-free region. Meanwhile, negative values of permittivity still appear at about 10^5–10^7 Hz but decrease as the irradiation dose increases. A resonance phenomenon appears in samples 0# and 1# around 0.68 MHz, where these two samples obtains the highest negative permittivity, respectively. The resonance phenomenon disappears in samples 2#, 3# and 4# at about 10^5–10^7 Hz, while the permittivity is still negative. It is believed that this resonance is the causality of the negative permittivity in nanocomposites [13]. Also, the permittivity of plasma and metals is dominated by their resonance due to a large number of free electrons according to the Drude model [14,15]. Results of Fig. 2 indicate that the resonance is not the only cause of negative permittivity in samples. Moreover, the resonances are not like a typical plasmon-resonance.

The dielectric response phenomenon that dielectric constant changes with frequency is called as dispersion phenomenon. It is well known that the dispersion phenomenon is mainly contributed to the multifarious polarization mechanisms including the electron displacement polarization, the ion displacement polarization, the orientation polarization of the intrinsic dipole moment and the interfacial polarization. There as on for results of Fig. 2 is inconsistent with that four basic traditional mechanisms. So, the mechanism of negative permittivity in silicon-based PiN diodes induced by irradiation needs further clarification.

Note that, electron irradiation will cause ionization damage and displacement damage in semiconductor materials or devices. Ionization damage creates free electron-hole pairs by disrupting electronic bonds, and displacement damage gives rise to atoms which are displaced from their usual lattice site, leaving behind a vacancy [16]. Defects induced by irradiation which have one or more levels in the bandgap can have a significant impact on the electrical properties of semiconductor devices.

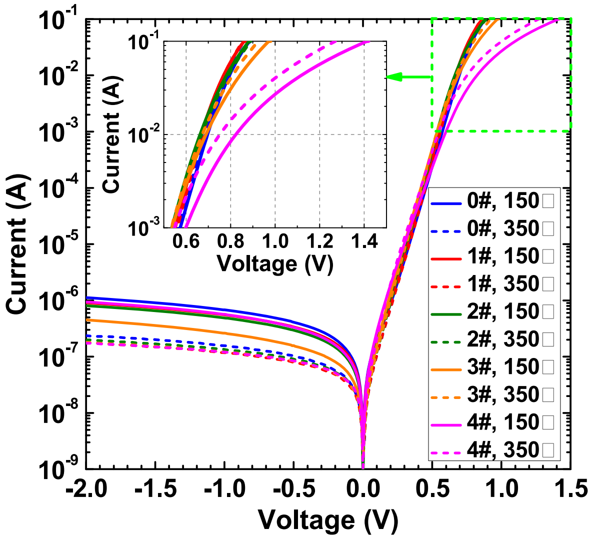

Fig. 4. I–V characteristics of samples after annealing.

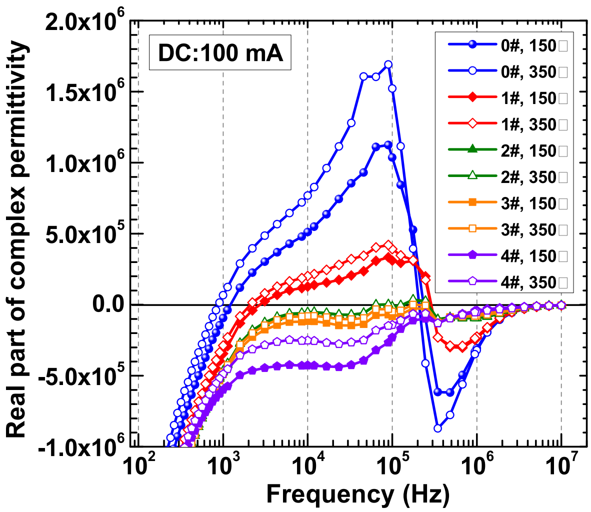

Fig. 5. Permittivity of samples after annealing.

To verify electrical properties of the irradiated devices, Fig. 3 shows I–V characteristics of all samples. The results reveal that the PIN diodes can still work normally after irradiation. As the electron irradiation dose increases, the forward on-state voltage at 100 mA is increased, and the increase of the forward on-stage voltage becomes significant when the electron dose reaches 5.4646×10^{15} e/cm^2, i.e., sample 4#. The reason may be that the electron irradiation reduces the lifetime in high-level injection conditions, which weakens the high-level injection (conductivity modulation) in the i-region. Besides, the leakage current at the reverse bias of all samples are almost the same, which indicates that the space-charge generation lifetime in samples may be not significantly influenced by electron irradiations. It can be found by comparing Figs. 2 and 3 that, variation of forward I–V characteristics for sample 4# is more significant than that for samples 1#, 2# and 3#, and changes in permittivity of sample 4# is more obvious that the other three samples. It indicates that the variation of permittivity has something corresponding relation with variation of forward I–V characteristics. Therefore, we guessed that defects in semiconductors induced by irradiation have something important impact on the generation and variation of the negative permittivity.

It is known that the annealing thermal treatment is widely used to induce annihilation of defects created by irradiation [17–20]. To identify the impact of defects on the permittivity, all the samples are annealed for 30 min at 150 °C and 350 °C in purified nitrogen (N2, 99.999%). Fig. 4 shows I–V characteristics of samples after annealing. It is found in Fig. 4 that, I–V characteristics can be recovered in a certain degree as annealing temperature increases, which is obvious in samples 3# and 4#. Besides, the leakage current can be lower after annealing at 350 °C than that after annealing at 150 °C in all samples. So, it can be inferred that there is a certain recovery of defects in samples.

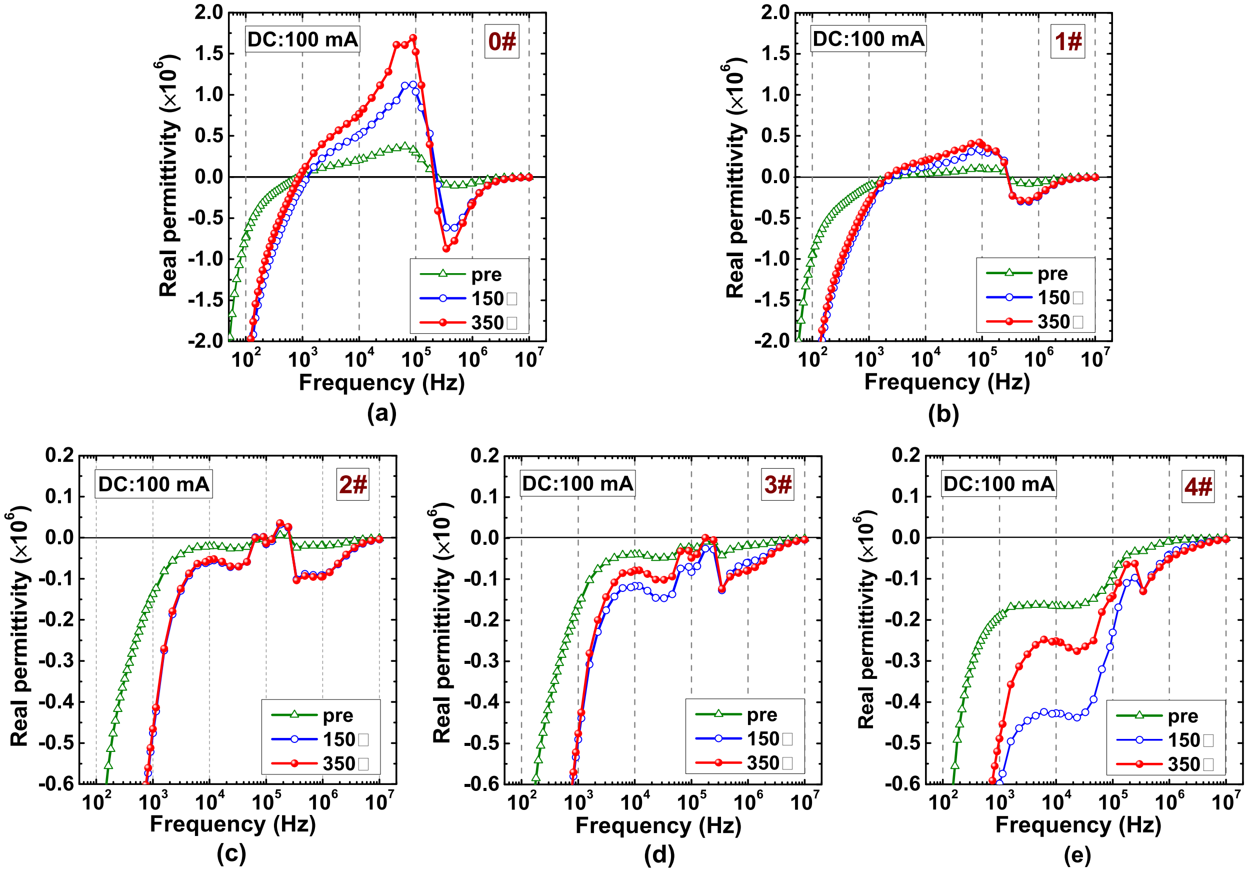

Fig. 6. Comparison of permittivity of each sample before and after annealing.

Fig. 5 shows the permittivity of samples after annealing. Beyond expectation, annealing treatments dose not recover the permittivity of all samples after irradiation, and the negative value platform of permittivity still exists in samples 2#, 3# and 4#. In fact, it can be learned by comparing Figs. 5 and 2 that the permittivity is not only greatly affected by irradiation but also by annealing treatments.

In order to better comparing the effect of annealing treatments on the permittivity, Fig. 6(a)-(e) show the relationship between frequency and the real part of complex permittivity for samples #0, #1, #2, #3 and #4, respectively. As shown in Fig. 6 (a) and (b), the dielectric response become stronger in samples #0 when the annealing temperature increases, which may be caused by recovery of intrinsic defects in sample #0. Besides, the annealing treatment is found be able to recovery the permittivity of sample 1#. However, cases in samples 2#, 3# and 4# are quite different from that in sample 1#. As shown in Fig. 6 (c), (d) and (e), it is interesting to find that the dielectric response of the platform values of permittivity in samples 2#, 3# and 4# become more negative after annealing. However, it is worth to point out that the negative platform values in samples 3# and 4# are smaller at 350 °C than that at 150 °C. This phenomenon is still unable to be fully explained by us. We tend to consider that the polarization mechanism behind the negative permittivity in silicon based PiN diodes is partly determined by irradiation induced defects, but what kind of defects is the main cause is still far beyond known.

4. Conclusions

In conclusion, negative permittivity in silicon-based PiN diodes can be induced by the electron irradiation. A negative value platform of permittivity can occur in the frequency range of about 10^3–10^5 Hz. Annealing treatments can recovery forward I–V characteristics in a certain degree, and recovery the permittivity in the case with a relatively low electron dose (1.0929×10^{14} e/cm^2). However, the dielectric response of the platform values of permittivity becomes more negative after annealing if the electron dose $\geq 5.4646 \times 10^{14}$ e/cm^2. The negative permittivity phenomenon in PiN diodes by electron irradiation is very novel, which is considered be caused by defects introduced by the electron irradiation, but more studies need be carried out for deep understanding mechanisms behind the novel phenomenon. Such a novel phenomenon may lead to some new applications, which may be compatible with the integrated circuits.

Credit author statement

Yun Li: Measure, analyses and writing. Zhimei Yang and Sijie Fan did many jobs in initial work (including experiment and analyses). Min Gong, Ping Su and Yao Ma: Review. Mingmin Huang: Writing- Reviewing and Editing.

Data availability

The data that support the findings of this study are available from the corresponding author upon reasonable request.

Declaration of competing interest

The authors declare that they have no known competing financial interestsor personal relationships that could have appeared to influence the work reported in this paper.

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