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Degradation of responsivity for photodiodes under intense laser irradiation

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ABSTRACT

Experiments of photodiodes irradiated by laser at various energy densities are performed in this study. The laser-induced changes in photocurrent and dark current are monitored, the degradation process of responsivity as a function of the laser energy density is obtained. Morphological examinations were done with a scanning electron microscope (SEM), and damaged depth was performed using a step profiler. The results indicate that the relative responsivity of photodiodes for He Ne probe beam gradually reduced with the increase of intense laser energy density. The mechanism of various degradation of responsivity was analyzed. The obvious decrease of responsivity mainly contributes to an increase in the surface recombination velocity caused by defects and thermal breakdown of PN junction. The results were significant for the study of interaction laser with material.

1. Introduction

Photodiode is one of the most important devices of modern optoelectronic systems, which is widely used in military, civilian, and other fields, owing to high sensitivity, low noise, small bulk, and light weight [1–3]. However, it is particularly susceptible to interference and damage when irradiated by an intense laser. Since the advent of high power pulse lasers, it is very important to study the laser-induced damage mechanisms of photodiode. In the past, lots of researches have been conducted. Kruer et al. reported laser induced thermal damage of infrared detector [4]. Li and Asta Katrine Storeboe performed the numerical analysis of the temperature field in PbS and HgCdTe detector, [5,6]. Chen demonstrated the laser damage threshold at the surface of HgCdTe [7]. Qi presented thermal process and surface damage of GaAs laser induced [8,9].

Electrical performance change is an important research aspect in the field of laser and photodiode interaction. In 1988, Acharekar reported laser-induced changes in current characteristics, breakdown voltage, light spot profiles and noise characteristics in silicon avalanche photodiode [10]. In 1990, Watkins reported the degradation of several electrical parameters in silicon photodiodes irradiated by short pulsed laser [11]. In 1991, Huffaker presented that the responsivity was correlated with laser-induced surface roughness and with the removal of the thin-films [12]. In 2002, Moeglin demonstrated a degradation of detector performances due to the large increase in defect concentration [13]. In 2004, Medvid reported the mechanism of recombination increase of CdTe crystal after irradiation with laser power [14]. In 2010, Asta Katrine Storeboe presented laser-induced nonequilibrium processes in intrinsic HgCdTe detector [15].

The laser-induced degradation of photodiodes responsivity has been experimentally observed, however, the specific process of responsivity change for PIN photodiode with laser energy density was not reported. Therefore, it is significant to further study the responsivity degradation process of photodiodes due to intense laser irradiation. In present study, we perform a detailed investigation of responsivity for PIN photodiode under 1064 nm and 10 ns laser irradiation. The degradation process of responsivity with the laser energy density is obtained and various possible mechanisms of degradation have been analyzed.

2. Theoretical analysis

For a silicon PIN photodiode, two major processes are involved, including the generation of photo carrier pairs and the separation of intense electric field from carriers. The spectral response R_d of PIN photodiode can be expressed as [16]

$$R_d = \eta \frac{p(1-r)\lambda q}{hc} \quad (1)$$

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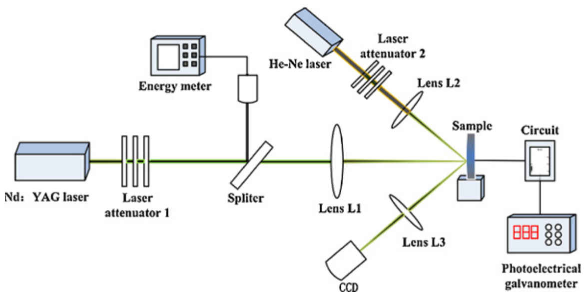

Fig. 1. Experiment installation diagram of the photodiode irradiated by laser.

Here λ is wavelength, *h* is Planck constant, *p* is probe beam power, *r* is reflection coefficient, *c* is light velocity, *q* is electron charge, *η* is the quantum efficiency of PIN photodiode.

Responsivity is related with the quantum efficiency, reflection coefficient, wavelength, device material and structure [17,18], and so on. Quantum efficiency and wavelength play an important role for responsivity of photodiode. Additionally, temperature has a certain effect on responsivity [19,20].

Assuming that the photodiode is maintained at a certain temperature, for a He Ne laser with given power, the responsivity is critical related with quantum efficiency. Quantum efficiency was strongly dependent on the device material and design, which dramatically decreases with increase of surface recombination velocity. The surface recombination velocity is closely associated with the surface condition. A great amount of defects on surface leads to an increase of surface recombination velocity. The quantum efficiency is also related with the absorption coefficient, quantum efficiency becomes bigger with the increase of absorption coefficient. Absorption coefficient is larger on rough surface than that on smooth surface.

3. Experimental research

The experimental configuration for irradiating PIN photodiodes was shown in Fig. 1. A TEM00 mode Nd:YAG laser with pulse duration of 10 ns, wavelength of 1.06 μm was employed for experiment. The output laser was focused on the surface of the sample by a lens L1 with focal length 150 mm, the spot radius of focused laser beam was ∼500 μm. A He Ne laser beam was used as a probe beam and by lens L2 focused onto the site to be damaged with a dimension smaller than Nd:YAG spot size. The incident laser energy density on the sample was controlled by adjusting the output energy and laser attenuator 1. The energy meter made real-time detection of the incident laser energy. The standard deviation of the pulse-to-pulse energy was 3% or less, and the energy reported here was the average value.

The PIN photodiode used in experiment was type GT102 with a 2 mm photosensitive surface size, which has standard antireflection coating to prevent reflection and to play a passivating role. The thickness of P, I and N region is 1.2 μm, 150 μm and 0.9 μm, respectively. The photodiode sample was placed on three-dimensional precision displacement platform. The surface morphology was real-time monitored by a CCD camera.

The photodiodes was connected to a 50 Ω load. The complete biasing circuits was shown in Fig. 2. At a bias voltage of 40 V, the photodiode was operating in the linear region for He Ne probe laser. The photocurrent and dark current signal were monitored by photodetectoral device, the photocurrent and the dark current were recorded, respectively before intense laser irradiation. And then the photodiode sample was irradiated by the Nd:YAG focused laser beam, the damage type was 1-on-1 pattern.

We define the relative responsivity as the ratio of the photocurrent for He Ne laser before laser irradiation to that after laser irradiation. When any laser-induced damage can be observed from the CCD camera, the photodiode was placed in air and cooled down to room temperature, the photocurrent and dark current were measured again. Subsequently, morphological examinations were done with a scanning electron microcope (SEM), and the damaged depth was performed using a step profiler. Under the same laser energy density, the measurements had been repeated ten times to obtain the average of the photocurrent and dark current. The experiment was performed at room temperature in air under normal atmospheric pressure.

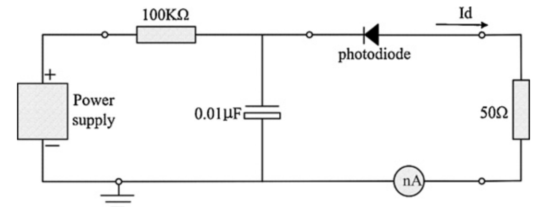

Fig. 2. Complete biasing measurement circuits diagram.

4. Results and discussion

The SEM image of morphology of the photodiodes was shown in Fig. 3. It can be seen that the damage degree became gradually serious with increasing laser energy density. Fig. 3(a)–(d) was the morphology photographs of the photodiode under laser irradiation at various energy densities.

When the photodiode was irradiated by laser at the energy density of 1.1 J/cm^2, the photodiode was slightly damaged. As shown in Fig. 3(a), there is fracture on the surface. The photodiode was somewhat seriously damaged under irradiation at the energy density of 6.9 J/cm^2. It can be seen from Fig. 3(b) that the damaged zone becomes broader, and there are some defects on the photodiode surface. When the photodiode was irradiated at the energy density of 17 J/cm^2, as shown in Fig. 3(c) and (g) that the photodiode was seriously damaged, there were more defects on the photodiode surface. The photodiode was more seriously damaged under laser irradiation at the energy density of 44 J/cm^2, it can be seen from Fig. 3(d) and its photosensitive surface exhibits a very large fusion pits.

The damage depth measurement was performed using a step profiler. As shown in Fig. 4(a)–(d), the damaged depth of the photodiode became big with the increase of laser energy densities.

While the photodiode is irradiated by laser at the energy density of 1.1 J/cm^2, as shown in Fig. 4(a), the damaged depth is ∼0.2 μm, with respect with the above mentioned, the antireflection coating has been damaged. Under irradiation at the energy density of 6.9 J/cm^2, the damaged depth is up to ∼2 μm, shown in Fig. 4(b), the P region has been damaged. While the photodiode is irradiated at the energy density of 17 J/cm^2, the damaged depth is ∼8 μm, shown in Fig. 4(c). Under irradiation at energy density of 44 J/cm^2, it can be seen from Fig. 4(d) that the damaged depth is ∼130 μm, I region has been seriously damaged.

The characteristic curve of relative responsivity versus laser energy density is illustrated in Fig. 5. It can be seen that the relative responsivity is gradually reduced with the increase of laser energy density.

When the photodiode is irradiated by laser at energy density of 3.2 J/cm^2 or lower, the relative responsivity is unchanged. When the photodiode is irradiated by laser at energy density greater than 4.6 J/cm^2, a slight decrease in relative responsivity is observed. The photodiode is irradiated by laser at energy density between 4.6 and 30 J/cm^2, the relative responsivity gradually decreases. There is a sharp decrease in relative responsivity of photodiode irradiated by laser at the energy density of 32 J/cm^2 or greater.