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OPTIMUM GUARD-RING FOR PLANAR InP/InGaAs PHOTODIODE: CHARACTERIZED WITH AFM, SCM and LBIC

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Abstract: To study the guard-ring suppression effect on the extension of the photo-sensitive area in planar-type front illuminated InP/InGaAs hetero-structure detector, the InGaAs photo detectors with different distances between guard-ring and PN junction were designed and fabricated. The actual distance between guard-ring and PN junction of the detector was calculated based on the atomic force microscopy (AFM) and scanning capacitance microscopy (SCM) measurements. The characteristics of the photo response of the detectors with guard-ring were carried out with laser beam induced current (LBIC) method. It was indicated that LBIC signal of the photo detector without guard-ring fit well with the exponential decay function, while that of detector with guard-ring followed the Gaussian distribution. The extension value of the photo-sensitive area decreased linearly as the distance between the guard-ring and PN junction decreased. It was concluded that the appropriate gap between the guard-ring and PN junction should be in the range of 7 to 12 μm.

Key words: scanning capacitance microscopy (SCM); laser beam induced current (LBIC); photo-carrier diffusion; guard-ring; InP/InGaAs
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AFM/SCM 及 LBIC 技术在平面型保护环结构 InGaAs 探测器设计中的应用

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摘要:为研究保护环结构对平面型正照射式 InP/InGaAs 探测器光敏元扩大现象的抑制作用,设计并研制了带有不同保护环-光敏元间距的 InGaAs 探测器.通过原子力显微镜(AFM)及扫描电容显微镜(SCM)获得了保护环与光敏元之间的实际距离.利用激光束诱导电流(LBIC)技术研究了带有保护环结构的 InGaAs 探测器的光响应特性.研究

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表明,无保护环结构的探测器的 LBIC 信号可以用指数衰减函数描述,而带有保护环结构的探测器的 LBIC 信号则遵从高斯分布.引入保护环结构后,器件光敏元的扩大量会随着保护环-光敏元间距的减小而线性减小.在器件设计中,比较合适的保护环-光敏元间距应介于 7 ~ 12μm 之间.

关 键 词:扫描电容显微镜(SCM);激光束诱导电流(LBIC);光生载流子扩散;保护环;InP/InGaAs

Introduction

InP/InGaAs/InP photo detector, especially the planar-type InP/InGaAs/InP photo detectors for the near-infrared (1 ~ 3μm) detection have the distinct advantages of low leakage current, high quantum efficiency, high reliability and room temperature operation. InGaAs detectors, especially the linear InGaAs detector array has found wide applications in many fields such as near-infrared spectroscopy, spectral characterization, agriculture monitoring, industrial process control, moisture measurement, biomedical analysis, and space remote sensing, etc [1~4].

However, in planar type InGaAs photodiode, the PN junction contact would collect not only all the photo excited carriers generated in the junction area but also part of the photo-carriers generated in a diffusion length around the junction area due to the lateral diffusion effect, which results in the extension of the photo-sensitive area. Especially in large scale detector arrays, as the pixel pitch became smaller, the extension of photo-sensitive area would result in cross-talk in photo detector arrays. The modulation transfer function (MTF) of the detector arrays and thus the precision of the image would be deteriorated[5]. Usually, the guard-ring structure between two neighbor pixels is used to suppress the extension of the photo-sensitive area at the cost of fill factor lost [6]. To study the photo responsive characteristics of the photodiode with guard-ring in planar-type front illuminated InGaAs detector arrays is meaningful for detector design.

In this paper, the planar-type front illuminated InP/InGaAs/InP hetero-structure photodiodes with different guard-ring to PN junction distances were fabricated with the sealed-ampoule method. The actual guard-ring to PN junction distance of the photodiode was calculated on the base of AFM and SCM measurements. The responsive characteristics of the photo detectors with guard-ring structure were investigated using LBIC technique.

1 Experimental details

The planar-type InGaAs photo detectors with guard-ring were fabricated on the NIN-type InP/InGaAs/InP hetero-structure materials with sealed-ampoule diffusion method using Zn_3P_2 as the diffusion source. The epitaxial material consisted of a 1μm Si-doped N-InP top layer with a doping concentration of about 5×10^{16} cm^{-3}, a 2.5μm InGaAs absorbing layer with a doping concentration of 5×10^{16} cm^{-3}, a 0.5μm N-InP buffer layer with a doping concentration of 2×10^{18} cm^{-3} and a 600μm S-doped InP substrate layer with a doping concentration of 2×10^{18} cm^{-3}. During device fabrication, a SiN_x layer deposed using PECVD acted as the diffusion mask, and the diffusion windows of the guard-ring area and PN-junction area were wet-etched using HF acid. In the PN-junction fabrication process, the guard-ring with a designed width of 10μm surrounding the PN-junction area was diffused simultaneously. Cross-section of the photodiode is shown in Fig. 1. The designed size of PN junction area was (45 × 40) μm^2. The designed distance D between the guard-ring and the PN-junction were 10, 15, 20 and 25μm, respectively. The photo responsive characteristics of the PN-junction area was carried out on a Micro LBIC system from SEMILAB Company. The pulsed laser of the LBIC system is at 980 nm with pulse frequency of 1kHz and the laser beam radius is 5μm. During LBIC measurement, the P contact and N contact of the guard-ring were short connected.

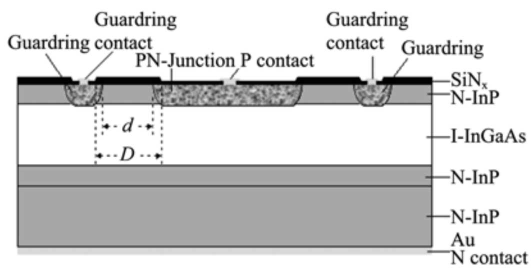

图 1 保护环结构平面 InGaAs 探测器的截面图
Fig. 1 Cross-section of the planar-type InGaAs photodiode with a guard-ring

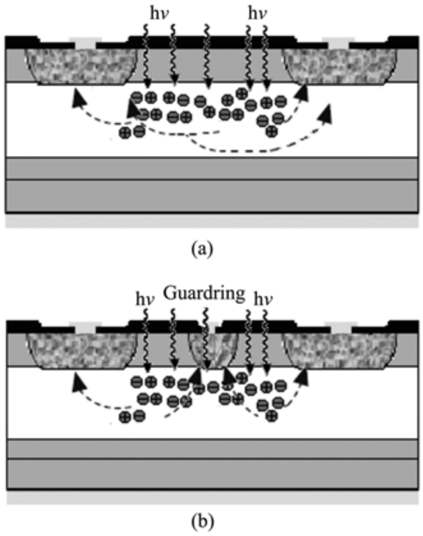

图 2 无保护环结构(a)及保护环结构(b)平面 InGaAs 探测器中光生载流子的扩散效应

Fig. 2 Photo-carrier diffusion effect in planar InGaAs photo-detectors without (a) and with (b) guard-ring

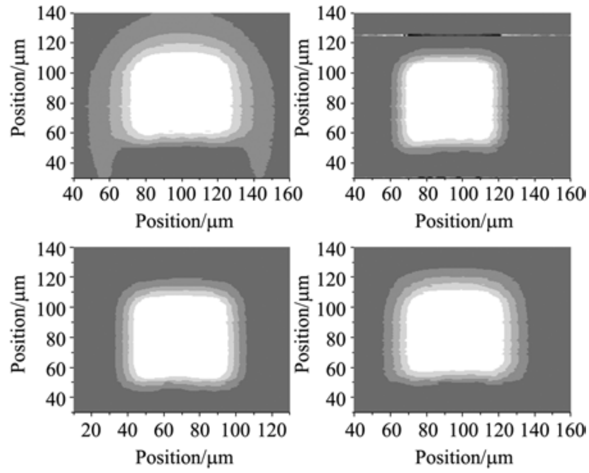

图 3 无保护环结构及保护环与 PN 结之间距离不同的平面 InGaAs 探测器的归一化 LBIC 信号等值灰度图

Fig. 3 Normalized LBIC signal gray isoline maps for detectors without guard-ring and with different distances between guard-ring and PN junction

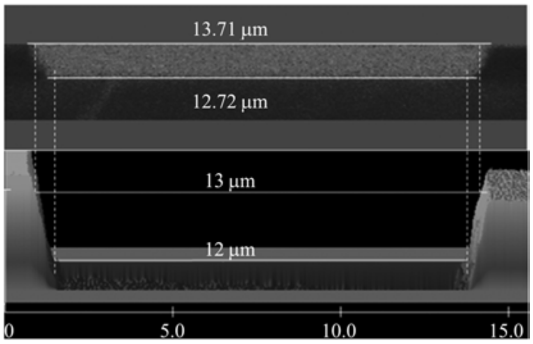

图 4 保护环扩散设计宽度为 10μm 时 SCM 测得扩散结区域(上)及 AFM 测得扩散窗口形状(下)

Fig. 4 SCM image of the guard-ring diffusion junction area (up) and AFM image of SiN_x diffusion mask with a designed 10μm wide diffusion window (down)

2 Results and discussion

For planar type InP/InGaAs/InP photodiode, the InGaAs absorption layer would absorb one incident photon and generate one pair of photo-carriers. Nearly all the photo-carriers generated in the junction area were collected by the PN junction contact due to the build-in electric field, while the photo-carriers generated around the junction area would diffuse freely, and were collected as the photo-carriers diffused near the junction area, as shown in Fig. 2.

Usually, the effective photo-sensitive area of a planar InGaAs detector is defined as the PN junction area plus the diffusion length of the photo-carriers. Thus the photo-sensitive areas of both neighbor pixels would extend for one diffusion length. However, as the pixel pitch reduced, the photo-carriers generated near one PN junction would diffuse freely and was collected by the neighboring PN junction, as shown in Fig. 2 (a), and the cross-talk appears.

As shown in Fig. 2 (b), after the guard-ring was brought in, part of the photo-carriers generated around the PN junction were collected, and the extension of the photo-sensitive area would be limited within the guard-ring area. Then the two neighbor pixels were isolated effectively.

The normalized LBIC signal gray isoline maps for detectors without guard-ring and with designed guard-ring to PN junction distances of 10, 15, 20μm were shown in Fig. 3. After bringing in guard-ring structure, the extension of the photo-sensitive area of the detector was greatly suppressed, and was limited in a smaller area as the designed guard-ring to PN junction distance reduced from 20μm to 10μm.

To quantitatively study the suppression effect of the guard-ring with different distances between guard-ring and PN junction, the AFM and SCM measurements were carried out.

The AFM image of a SiN_x diffusion mask with a designed 10μm wide diffusion window is shown in Fig. 4. Due to the side etching effect of HF acid, the SiN_x

diffusion mask was etched into an invert-trapezoid-shaped diffusion window with a top width of 13μm and a bottom width of 12μm. It was indicated that the actual distances between guard-ring and PN junction would decrease by about 2μm.

Meanwhile, during the diffusion process, Zn element would diffuse both laterally and vertically. Scanning Capacitance Microscopy (SCM) had been applied in studying the dopant profiles across junctions in InP/InGaAs hetero structure materials successfully [7,8]. To study the across junction distribution, the photodiode was cleaved and the SCM measurement was carried out. And the SCM iamge of the guard-ring junction area is shown in Fig. 4. The width of the across junction was about 13μm, which indicated that the actual distance between the guard-ring and the PN-junction would decrease about 3μm, as shown in Fig. 1. And d decreased to about 7, 12, 17 and 22μm, respectively.

As shown in Fig. 5, for the photo detector without guard-ring, the photo induced carriers in relative long distance from the PN junction edge would diffuse laterally and were collected by the junction contact. And this lateral diffusion effect was greatly reduced after the guard-ring was brought in. As the guard-ring to PN-junction distance reduced, the suppression effect increased even more.

The exponential decay function is usually used to describe the relationship between LBIC signal and the laser beam-to-junction distance, and is given as follows[9]

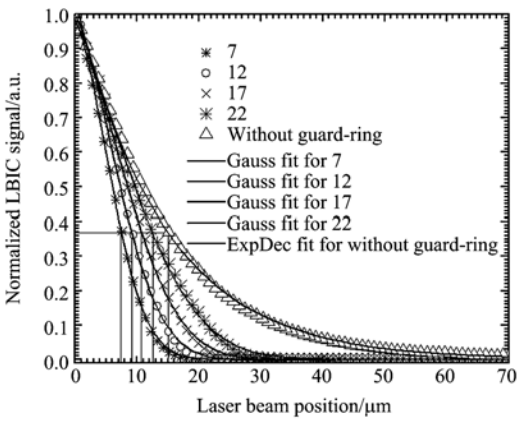

图5 不同保护环与 PN 结间距探测器结区边缘的归一化 LBIC 信号随光束位置的变化

Fig. 5 Normalized LBIC signal near the edge of the PN junction varying with the laser beam position for different guard-ring to PN-junction distance

$$I_{\mathrm{LBIC}}(x) = I_0 + A\mathrm{e}^{-x/L} \quad , \qquad (1)$$

where I_{LBIC}, x, L, A and I_0 are the LBIC signal, the laser beam-to-junction distance, photo carrier diffusion length, proportionality constant and constant, respectively. As shown in Fig. 5, the exponential decay function fit well with the LBIC signal of photodiode without guard-ring. The fitted diffusion length L was about 14.44μm.

However, as the guard-ring was brought in, part of the photo-carriers generated around the PN junction would be collected by the short-connected guard-ring. The exponential decay function was not suitable any more.

Instead, as shown in Fig. 5, the LBIC signal of the photodiode with guard-ring fit well to Gaussian function. It was indicated that Gaussian function might be a suitable solution, which is shown as follows

$$I_{\mathrm{LBIC}}(x) = I_0 + \frac{A}{w\sqrt{\pi/2}}\mathrm{e}^{-2(x-x_C)^2/w^2} \quad , \qquad (2)$$

where I_{LBIC}, x, w and x_C are the LBIC signal, the laser beam-to-junction distance, designed guard-ring to PN junction distance and the peak I_{LBIC} value position, respectively. Both I_0 and A were different fitted constants for different guard-ring to PN-junction distances. Usually, the photo-carrier diffusion length L is defined as the position at which the LBIC signal decreased to 1/e of the peak value. In function (2), I_0 is a small value compared to I_{LBIC} and could be ignored, and the value $A/w\sqrt{\pi/2}$ is also constant. The photo-carrier diffusion length of the photodiode with guard-ring is defined as follows:

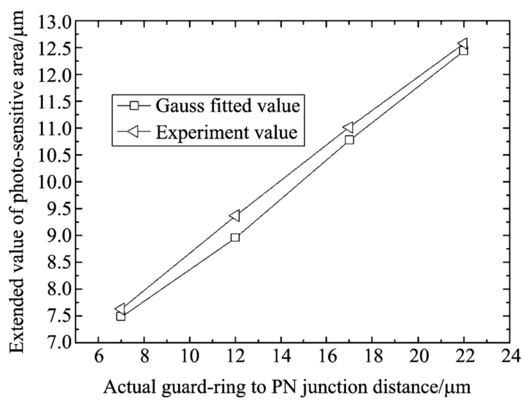

图6 光生载流子扩散长度随保护环与 PN 结间距的变化

Fig. 6 Photo-carrier diffusion length versus guard-ring to PN junction distance

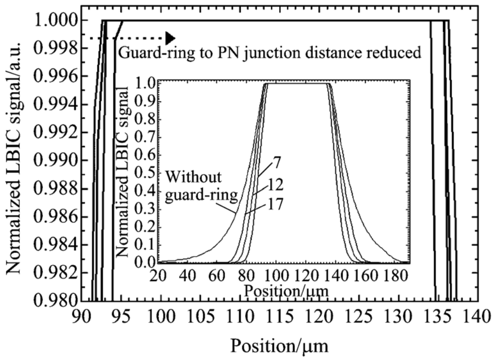

图 7 无保护环结构及保护环与 PN 结之间距离不同的平面 InGaAs 探测器的归一化 LBIC 信号曲线

Fig. 7 Normalized LBIC signal for detectors without and with different guard-ring to PN junction distances

$$L = x_C + w/\sqrt{2} \quad . \tag{3}$$

According to the fitted results, the photo-carrier diffusion length for the photodiode with different guard-ring to PN-junction distances were about 7.49, 8.96, 10.78 and 12.45μm, respectively, as shown in Fig. 6.

Choosing the position at which the LBIC signal decreased to 1/e of the peak value as the extension value of the photo-sensitive area, the experimental value and Gauss fitted value are listed in Fig. 6. It is shown that the extension value of the photo-sensitive area would decrease linearly down to a value which went beyond the system limitation as the guard-ring to PN junction distance decreased. From the discussion above, it is indicated that to design planar-type front illuminated InGaAs detector arrays with guard-ring, as the pixel pitch is reduced, the guard-ring to PN junction distance should be as small as possible. However, one of the basic principles in detector design is that the guard-ring structure should not affect the signal of the PN junction area itself. As shown in Fig. 7, the PN junction area of a detector with a guard-ring to PN junction distance of 7μm reduced by about 4μm compared to the detector without guard-ring.

Thus based on the experimental data and system precision to date, the appropriate guard-ring to PN junction distance should be between 7 and 12μm.

3 Conclusions

The planar-type InP/InGaAs/InP hetero-structure photodiodes with different guard-ring to PN junction distances of 10, 15, 20 and 25μm were fabricated with sealed-ampoule method. According to AFM and SCM measurement, the actual guard-ring to PN junction distance of the photodiode was calculated as 7, 12, 17 and 22μm, respectively. The LBIC signal of the photo detectors was measured. It was indicated that LBIC signal of the photodiode without guard-ring fit well with the exponential decay function, while the LBIC signal of the photodiode with guard-ring could be described by the Gaussian function. Based on the Gaussian function, the photo-carrier diffusion lengths of photodiodes with guard-ring were deduced as $L = x_C + w\sqrt{2}$. The extension value of the photo-sensitive area would decrease linearly as the guard-ring to PN junction distance decreased.

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