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Determination of minority carrier lifetime in a finite base HgCdTe photodiode: Pulse recovery technique

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Abstract: An experimental study of the minority carrier lifetime in a finite base HgCdTe n^+-on-p photodiode using pulse recovery technique (PRT) is presented in this paper. The reverse recovery storage time (t_s) is functions of the forward current I_F and reverse current I_R. Average minority carrier (electron) lifetimes (τ_n) calculated from t_s and I_F/I_R strongly increases with decreasing ratio of the base thickness to the diffusion length. The minority carrier (electron) lifetime extracted from the conventional theory is approximately 28 ns at 77 K, much less than the value of 51 ns obtained when short base effects are considered in the analysis. This reveals that the base thickness of the photodiode is an important parameter for the minority carrier lifetime measurement using PRT. The infinite base assumption is valid only if the base thickness is larger than about three times the diffusion length of minority carriers.

Key words: HgCdTe, minority carrier lifetime, pulse recovery technique, diffusion length

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脉冲恢复技术测量有限宽基区 HgCdTe 光电二极管少子寿命

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摘要:利用脉冲恢复技术测量了有限宽基区 n^+-on-p 光电二极管中的少子寿命.实验发现，反向恢复时间同正、反向电流的大小有关.从恢复时间 t_s 与 I_F/I_R 函数关系提取的少子寿命随着基区厚度与少子扩散长度比值降低而明显增大.在77 K时，采用传统方法脉冲回复技术提取的少子寿命为28 ns，而当考虑短基区效应时，所提取的少子寿命为51 ns. 这表明HgCdTe光电二极管的基区厚度与少子扩散长度比值是采用脉冲恢复技术测量少子寿命技术中的一个重要参数.只有当基区厚度大于三倍少子扩散长度时，传统方法中无限基区厚度的假设条件才成立.

关 键 词:碲镉汞;少数载流子寿命;脉冲恢复技术;扩散长度

中图分类号:TN215 **文献标识码**:A

Introduction

HgCdTe is the preferred material for detectors and focal plane arrays over a broad range of the infrared spectrum [1-3]. At present, pn junction structure is still widely used in the preparation of HgCdTe infrared detectors. The recombination lifetime of minority carrier injected across pn junctions plays a key role in determining device performance [4]. Previous study results show that the lifetime obtained techniques with different testing is widely distributed in the order of μs ~ ns range [5] for samples with different Cd composition,

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size, and growth conditions. Since the material property may be changed during the formation of pn junction, the parameters of HgCdTe raw material cannot be applied to estimate the properties of pn junction devices. In order to determine the minority carrier lifetime in HgCdTe photodiode, the measurements must be carried out on the actual devices thus the extracted parameters can be utilized in device design and simulation.

Many methods have been developed to measure the minority carrier lifetime for other material devices such as: short-circuit current, open-circuit voltage decay (OCVD), pulse recovery technique (PRT) etc.[6] Among the techniques, PRT is one of the most commonly used methods for determining lifetime in pn junction diodes, which was first used to analysis Si diode in 1954[7]. By monitoring the junction current in a diode as it is biased from forward to reverse bias in a diode, the average minority carrier lifetimes (τ) can be calculated from t_s and I_F/I_R. This theory is based upon a basic assumption, that is, base thickness (W) of the photodiode is infinite. However, this assumption is valid only if W is much larger than the diffusion length of the minority carrier. In this paper we present a theory of PRT in HgCdTe photodiode taking into account its finite base. The minority carrier continuity equation for a photodiode has been used to obtain the initial boundary condition. We find that the infinite base approximation is valid only if W is larger than about three times the diffusion length of minority carriers.

1 Theory

1.1 Theory of pulse recovery technique

Considering a n^+-on-p photodiode p-substrate of conceptual model of the PRT is shown in Fig. 1(a) and Fig. 1(b). Figure 1(c) shows variation of the concentration of electrons in p region of HgCdTe pn junction device. When the n^+-on-p photodiode is rapidly switched from forward into reverse bias, excess minority carriers generated from forward bias injection must recombine before current flowing through the diode can drop to near-zero[8]. The reverse current signal observed can be divided into two different phases. The first phase (Fig. 1(b)①) is the constant recovery current component lasting for t_s which is defined as charge storage time, as is shown in Fig. 1(c)①→②. The reverse current then drops off quasi-exponentially to near zero subsequently (Fig. 1(b)②) during the time t_f, as is shown in Fig. 1(c)②→③.

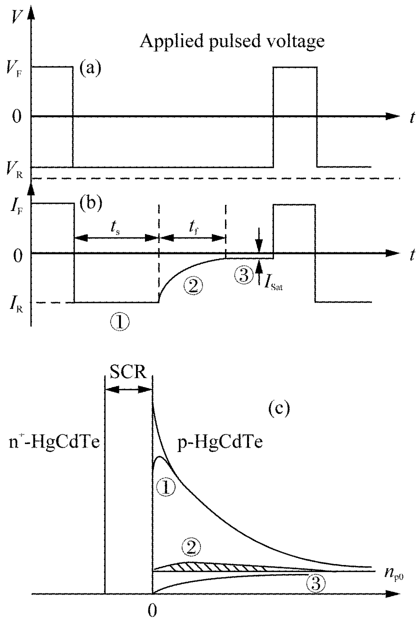

Fig. 1 HgCdTe photodiode current response versus time in the PRT (a) the chang es of bias voltage with time, (b) time dependence of the current response, and (c) the carrier density in p region at different phase
图1 脉冲恢复技术中碲镉汞光电二极管的电流时间特性（a)偏压和时间的关系，(b)电流响应，(c)不同时间阶段p区载流子的浓度变化

As discussed above, the current recovery progress of the photodiode has been related into the attenuation progress of the excess minority carrier introduced into the base region by forward bias. The electron concentration will be reduced by two ways, one is the recombination with holes in p-HgCdTe, and the other is the electrons flow away from the junction to constitute the reverse current. By monitoring the junction current in a diode as it is switched from forward to reverse bias in a diode, the reverse current through the diode may be observed as a function of time. The storage time and the forward-reverse current are then related to the lifetime. The lifetime can be calculated using both constant current phase and non-constant current phase. However, the constant current phase can be more easily observed and used in the actual testing progress, and more suitable for the calculation of the minority carrier lifetime in the base region. We treat the device as an essentially one-dimensional structure. As derived by Green[9], an expression for the transient voltage decay can be reached by using the minority carrier continuity equation for the base of the diode, given as:

$$\mathrm{d}Q/\mathrm{d}t = -I_\mathrm{R} - Q/\tau \quad , \quad (1)$$

where Q, I_R and τ are the storage excess minority carrier charge in the quasi-neutral base region, reverse current, and minority carrier lifetime, respectively. The solution to Eq. (1) using the boundary conditions $Q(t=0)=I_\mathrm{F}\tau$ and $Q(t=t_\mathrm{s})=0$ can be expressed as:

$$t_\mathrm{s} = \tau \times \ln(1 + I_\mathrm{F}/I_\mathrm{R}) \quad , \quad (2)$$

where I_F is the forward current. $\ln(1+I_\mathrm{F}/I_\mathrm{R})$ linear with time, so the minority carrier lifetime can be calculated from the slope of the line fitted to Eq. (2).

1.2 The finite base HgCdTe diode

The traditional PRT theory assumes a lightly doped region of the thickness W, such that $W>>L_e$, the minority carrier diffusion length. For the case of narrow base approaches to the minority carrier diffusion length, the assumption that the boundary condition $Q(t=0)=I_\mathrm{F}\tau$ is not accurate. This is due to that the excess carrier at $x=W$ will be removed from the base according to the boundary condition, that is, $n_p(W)=n_{p0}$. The electrons $Q(t=0)$ accumulated in the base region will be less than $I_\mathrm{F}\tau$. Therefore, the minority carrier lifetime calculated from Eq. (2) will be too small. Taking into this account, the excess electron charge stored in the base region under the positive bias must be corrected. The distribution density of the carrier can be written as [10]:

$$n_p(x) = n_{p0} + [n_p(0) - n_{p0}]\frac{\sinh\left(\frac{W-x}{L_\mathrm{e}}\right)}{\sinh\left(\frac{W}{L_p}\right)} \quad . (3)$$

The charge stored in the base region at $t=0$ can be obtained by integrating the formula (3):

$$Q(t=0) = \int_0^W (n_p - n_{p0})\,\mathrm{d}x \; m\tau_\mathrm{n} I_\mathrm{F} \quad , \quad (4)$$

$$m(W/L_\mathrm{e}) = \frac{\mathrm{e}^{(W/L_\mathrm{e})} + \mathrm{e}^{(-W/L_\mathrm{e})} - 2}{2\sinh(W/L_\mathrm{e})} \quad . \quad (5)$$

Solving the Eq. (1) using the new boundary condition $Q(t=0)=mI_\mathrm{F}\tau$ and $Q(t=t_\mathrm{s})=0$ the relationship between the recovery time t_s and current ratio $I_\mathrm{F}/I_\mathrm{R}$ is:

$$t_\mathrm{s} = \tau \times \ln(1 + m \times I_\mathrm{F}/I_\mathrm{R}) \quad . \quad (6)$$

Comparing Eq. (2) with Eq. (6), it is clear that m approaches 1 when the W/L_e tends to infinity, and therefore, Eq. (6) have the same form as Eq. (2). Thus, the thick base region is the basis of the boundary conditions used in Eq. (2). When W is less than or approximately equal to L_e, the value of m will no longer be equal to 1, and the calculation of the minority carrier lifetime will be influenced consequently. Figure 2 shows the relationship between m and W/L_e. It can be seen that when W/L_e increases from 0 to 10, the value of m increase from 1 to 10. Thus the minority carrier lifetime calculated from PRT will decrease with the increasing of W/L_e within a certain range of the ratio of W to L_e.

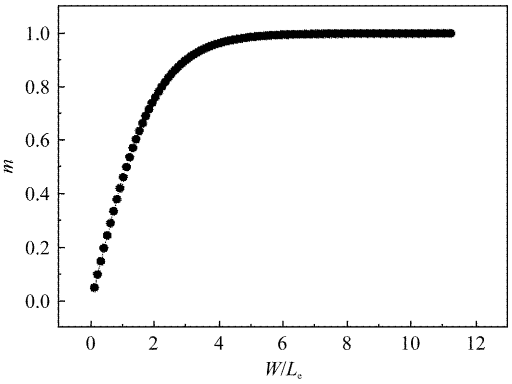

Fig. 2 The relationship between m and W/L_e
图 2 W/L_e 取不同值时 m 函数值的变化关系

2 Experiments

The PRT experiment scheme is shown in Fig. 3. The HgCdTe photodiode was grown by molecular beam epitaxy on (100) GaAs substrate with a buffer layer of CdTe. The pn junction was formed by boron ion implantation into the p-type $\mathrm{Hg_{0.5814}Cd_{0.4186}Te}$ layer, resulting in an abrupt $\mathrm{n^+}$-on-p structure[11]. The width of p and $\mathrm{n^+}$ regions are about 7 and 1 μm, respectively. The active area of HgCdTe photodiode is 50 μm × 50 μm. The mobility of electron in p-type HgCdTe is about 189 $\mathrm{cm^2/Vs}$. The sample was mounted in liquid nitrogen Dewar with temperature kept at about 77 K for measurement. The sub-nanosecond pulser signal was generated by Agilent 33 250 A. The sample under test is connected via BNC coaxial cable in series with a 50 Ohm resistor. Both signals from the pulse source and the HgCdTe photodiode were monitored and recorded with an Agilent Infiniium 54 832 B.

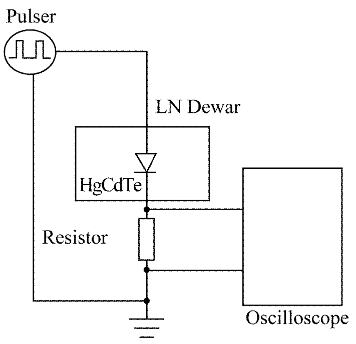

Fig. 3 Schematic of the experimental setup
图3 脉冲恢复技术实验装置图

3 Results and discussion

Figure 4 shows the experimentally recorded reverse recovery current transients from HgCdTe photodiode for various values of I_R. The forward current I_F is held approximately constant by fixing the forward bias voltage. The reverse current will go back to the cut-off state as it is switched from forward to reverse bias. This indicates that the minority carrier stored in the photodiode will disappear gradually. As the reverse bias increases, the reverse current is found to increase gradually, while the charge storage time t_s and recovery time t_f are found to decrease dramatically. The dependence of the storage time amplitude on the current ratio I_F/I_R is plotted in Fig. 5. The slope of 28, obtained by linear fitting using Eq. (2) to the experimental data in linear coordinate, indicates that the lifetime of excess electrons accumulated in the base is 28 ns.

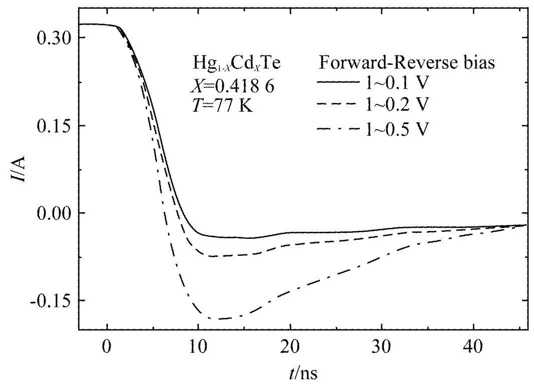

Fig. 4 Reverse recovery current transient of the diode as a function of initial reverse bias
图4 不同反向偏压下，反向恢复电流的时间特性

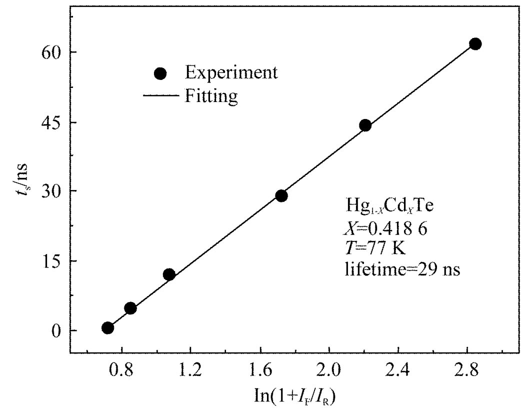

Fig. 5 The storage time *vs* the current ratio I_F/I_R. The circle points are the experimental results and the solid line represents the curve fiting to Eq. (2)
图5 储存时间与 I_F/I_R 的关系. 实心点代表实验数据,实线代表利用式(2)拟合得到的结果

Since the base thickness of the photodiode studied in this work approaches or less than the electron diffusion length reported in the literature [12] or calculated via the Einstein relation, the minority carrier lifetime calculated from the reverse recovery characteristics should be corrected by the theory considering the narrow base effect, that is, the ratio of base thickness to the electron diffusion length. Substituting Einstein relation[13] Eqs. (7) and (8) into Eq. (5), the minority carrier lifetime obtained is 51 ns by numerically solving the differential Eq. (6).

$$D = \frac{\mu kT}{q} \quad , \quad (7)$$

$$L_e = \sqrt{D\tau} \quad , \quad (8)$$

where D, μ, k, T are electron diffusion coefficient, mobility, Boltzmann constant, and temperature, respectively. The large difference (more than 2 times) in lifetimes measured by PRT with and without considering the short base effect indicates that W/L_e is an important parameter in determining the lifetimes. In Fig. 6, we also present the relationship between the minority carrier lifetime and W/L_e with the same experimental data. Comparing the lifetime at $W/L_e = 3.4$ and 0.24, we ound that, lifetime changes from 30 to 129 ns (4 times increase). This significant enhancement of the lifetime could be attributed to the storage of charge in the base region increasing with the increasing of W/L_e. Under the same conditions of t_s and current ratio I_F to I_R, the larger the number of electrons accumulated in the base region, the shorter the lifetime is. As a result, the infinite base approximation is valid only if W is larger than about three times the diffusion length of minority carriers. This conclusion is consistent with m function character shown in Fig. 2.

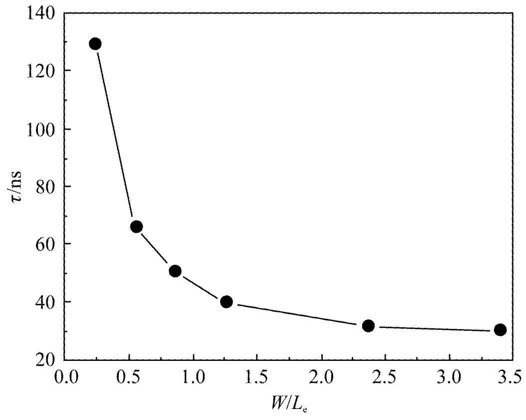

Fig. 6 The relationship between minority carrier lifetime and W/L_e. The solid line is for eye guide
图6 少子寿命同基区厚度与少子扩散长度比值的关系

The abovementioned observations underscore the importance of studying photodiode minority carrier lifetime as a function of W/L_e. Since $W \leqslant L_e$ reduces the storage charge accumulated in the base region, the minority carrier lifetime using conventional PRT will be estimated too small. In addition, the previous studies also showed that the recombination lifetime has been associated with a surface recombination[14]. The short base region could lead to increased surface recombination, thus reducing the values of the minority carrier lifetime. The measured lifetime value calculated in this paper is the combined effect of the bulk and surface components, which is called effective lifetime. The analysis of the influence of surface recombination on calculated lifetime will be studied later.

So far we have only concerned with substrate minority carrier recombination in the n^+-on-p photodiode. Also, the minority carrier will recombine in the heavily doped n^+ emitter[15]. The emitter lifetime is generally much lower than the base lifetime. Therefore, the minority carrier recombination in emitter will have a significant influence on the PRT measurement. However, it is should be noted that the emitter in this measurement is much more heavily doped (1×10^{17} cm^3) than the base (1×10^{15} cm^3). Generally, this effect results in a shorter lifetime shorter than the real lifetime appreciably under high injection conditions, while it can be minimized at low and moderate injection levels[16].

4 Conclusions

The major conclusion of this work is that the $W \leqslant L_e$ will influence the calculation of minority carrier lifetime. This is demonstrated by the experiment study of the minority carrier lifetime in a finite base HgCdTe n^+-on-p photodiode using PRT. The recombination lifetime considering the short base effect was found to be about a factor of 2 higher than that of conventional PRT. The infinite base approximation is valid only if W is about three times larger than the diffusion length of minority carriers. Given the fact that there has been little previous investigation of minority carrier lifetime in HgCdTe photodiode as a function of diffusion length vs. base thickness, this work raises the possibility that thin base effect may be partly responsible for poor effective minority carrier lifetimes and limited performance obtained in many previous HgCdTe junction devices.

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理较为复杂,但定性来说,缺陷密度增加,内耗增加,噪声随振动能量的变化系数也会增大.

以上只考虑了最简单的情况,实际的碲镉汞光导器件中存在大量杂质和缺陷,这可能是内耗偏大的原因.更符合实际情况的阐述是:随机振动的能量被碲镉汞材料中的晶格、杂质和缺陷吸收,增大了它们做为散射中心对载流子的碰撞几率,从而改变了器件电阻,当外界对器件施加恒定的工作电流时,器件两电极间形成了和振动能量成线性相关的噪声电压.

3　结论

研究了碲镉汞中波光导器件的振动噪声,发现了在随机振动时,振动噪声和振动强度是分段线性相关的,并利用声子理论给出了相应的解释.认为振动能量改变了碲镉汞材料中的晶格、杂质和缺陷对载流子的碰撞几率,影响了中波光导器件的电阻,产生了振动噪声,并利用吸收声子的量子性,很好的解释了实验中发现的分段线性关系.

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