Experimental determination of minority carrier lifetime and recombination mechanisms in MCT photovoltaic detectors

Haoyang Cui, Naiyun Tang, Zhong Tang
School of computer and information engineering,
Shanghai University of Electric Power, 2103 Pingliang Road, Shanghai 200090, China, cuihy@shiep.edu.cn

***Abstract*—This paper presents an experimental study of minority carrier lifetime and recombination mechanisms in HgCdTe photodiode. The excitation light source is a wavelength-tunable pulsed infrared laser. A constant background illumination has been introduced to minimize the effect of the junction equivalent capacitor and the equivalent series resistance. The slow decay of the photo-generated voltage is recorded by a storage oscilloscope. By fitting the exponentially decay curve, the time constant has been obtained which is regarded as the photo-generated minority carrier lifetime of the HgCdTe photodiode. The experimental results show that the carrier lifetime is in the range of 18 ~ 407 ns at 77 K for the measured detectors of four compositions. It was found that the Auger recombination process is more effective for low Cd composition while the radiative recombination process became more important for high compensated materials. The Shockley-Read-Hall (SRH) recombination processes could not be ignored for all Cd composition.**

Keywords- HgCdTe, minority carrier lifetime, open circuit photvoltage, Cd composition

I. INTRODUCTION

The minority carrier recombination lifetime has been known to be a based parameter of the semiconductor devices. Even though HgCdTe is used extensively for photovoltaic detectors, however, there is still a great deal of ambiguity issues, such as the minority carrier lifetime and the governing recombination mechanisms [1]. This is because of the instability of HgCdTe, which the material property may be changed during the process of the formation of *pn* junction. Therefore, the parameter of the raw material can not be applied to estimate the properties of *pn* junction devices. Moreover, there are great differences between the actual parameters and the design parameters such as trap concentration, carrier concentration, the junction depth, the junction width in conventional techniques. These factors have a lot of uncertainties effects on the *pn* junction. In order to determine the minority carrier lifetime, the measurements must be carried out on the actual devices then the extracted parameters are applied in devices design and simulate. Many measurements have been developed to determine the minority carrier lifetime such as: short-circuit current, open-circuit voltage decay (OCVD), pulse recovery technique etc [2,3]. However, the minority-carrier lifetimes of HgCdTe material are in nanosecond range, these methods not suit to measure such short lifetime.

The purpose of this paper is to measure the minority carrier lifetime using an improved photo-induced OCVD measurement technique which compensates the effects of the junction equivalent capacitor and the trap center on the measurements. The experiments results show that the carrier lifetime is in the range of 18 ~ 407 ns at liquid nitrogen temperature for the measured detectors of four compositions. From the experiment results, the governing recombination mechanisms are obtained by analyzing the free carrier recombination theory.

II. EXPERIMENTAL SETUP

The incident pulse laser having wavelength tuning range 2.3 ~ 10 μm was provided by an commercial optical parametric oscillator (OPG) and difference frequency generator (DFG) which were pumped by a picosecond Nd:YAG laser. The Laser delivered pulse of 30 ps in duration at a frequency 10 Hz. We could approximately these pulses as δ function illumination on the detector at $t = 0$, therefore, the influence of the falling time was avoided. In order to minimize the effect of the junction equivalent capacitor and the equivalent series resistance on the carrier lifetime measurements, we inducted an Oriel QTH lamp as the steady-state bias light source. A saturated steady-state of the *pn* junction output electric signal would be reached by turning the intensity of the bias light. Then the pulsed laser was illuminated on the sample and by recording the OCVD and fitting to the exponential decay curve, we could determine the minority carrier lifetime.

All HgCdTe samples were grown by MBE on GaAs substrates with CdTe buffer layers and an abrupt n^+-p structure were formed by the ion implantation of B^+ in p-type HgCdTe. As ZnS films were formed on the HgCdTe surface for passivation, the measured lifetime values were not influenced by the surface treatment. The structure of the HgCdTe photovoltaic detectors is shown in the inset of figure 1.The composition of $Hg_{1-x}Cd_xTe$ in our experiments are $x = 0.231$ ($\lambda_{Eg} \sim 8.6$ μm), $x = 0.305$ ($\lambda_{Eg} \sim 4.6$ μm), $x = 0.343$ ($\lambda_{Eg} \sim 3.7$ μm) and $x = 0.418$ ($\lambda_{Eg} \sim 2.9$ μm). The detectors were processed into 50×50 μm^2 area mesa structures. The photo-generated voltage on a *pn* junction has been recorded by a storage oscilloscope.

III. RESULTS AND DISCUSSION

A. minority carrier lifetime

Depending on the intensity of the excitation source, three different regions of the photovoltaic decay curve can be distinguished as high level injection, intermediate injection and low-injection [4]. The device actual is in low-injection condition. In this condition, where the excess minority carrier concentration is less than the equilibrium minority carrier concentration, the photovoltaic decay curve approaches exponential time dependence:

$$V_{oc} = \frac{kT}{q}\left[\exp\left(qV(0)/kT\right) - 1\right]\exp(-t/\tau) \tag{1}$$

which $V(0)$ is the open circuit voltage at the termination of excitation. Best fitting to the decay of the photovoltaic curve was realized with a second-order exponential decay function. The characteristic decay times were τ_1~2 μs and τ_2~35 μs. However, from the previous analysis, these long decay time constants were not the lifetimes of minority carriers but the presence of junction equivalent capacitor and trap energy level effects on excess carrier's relaxation.

The steady-state output photo-voltage of the *pn* junction would increase with the bias incident intensity increasing. The decay time constants of photovoltaic response induced by the pulsed laser were becoming shorter and the transient peak amplitude were decreasing with the incident intensity increasing. These phenomenons could be attributed to the junction equivalent capacitor and the trap center energy level effects on the decay curves became smaller when the bias light illuminated on the devices. The junction equivalent capacitor, equivalent series resistance and the trap center would be compensated or even cancelled under strong bias light condition. In this case, the photo-excited carriers annihilated by the recombination in base region and this photovoltaic decay time constant was related to the minority carrier lifetime. Since the values of the resistance and the carrier lifetime are much larger in the *p* region than in the n^+ region, and the photo-generated carriers in the emitter are about one percent of the carriers generated in the base, therefore, we can assume that the carriers stored in the base play a dominant role in the OCVD process [5].

The photo-excited OCVD decay curve was fitted with the expression in Eq (1), and the lifetime magnitude of the minority carrier in *p* region was determined to 190 ns. Using the method mentioned above, the minority carrier lifetime of the HgCdTe photodiode with different composition could be obtained. The results of the same composition came from different units of one array. There are distinctions between the different units of one array because the HgCdTe raw material is non-uniformity or the growing process can not be mastered. The excess carrier lifetimes extracted from our experiments are reasonable because of the lifetime magnitude consist with others results [2]. Generally speaking, there is a certain difficulty to precise measuring minority carrier lifetime. Even for the silicon material, the minority carrier's lifetime of accuracy scope is ±135% in different laboratory in American Society for Testing and Materials (ASTM) [6]. Therefore, it is acceptable that there is some divaricating in the lifetime experiment measuring of HgCdTe photodiode.

B. determination of recombination mechanism

The minority carrier lifetime τ obtained by the experiments are the present of radiative, Auger and SRH recombination mechanisms, therefore, the dominant recombination can be determined by analyzing the relationship of these mechanisms [7] which is given by:

$$\frac{1}{\tau}=\frac{1}{\tau_{\mathrm{A}}}+\frac{1}{\tau_{\mathrm{Rad}}}+\frac{1}{\tau_{\mathrm{SRH}}} \qquad (2)$$

The radiative recombination lifetime τ_{Rad} and Auger recombination lifetime τ_{A} in HgCdTe material with different doping concentration can be obtained by theory calculation. There are four doping concentration HgCdTe material, only three of which are shown in Fig 1.

From Fig 1, one can descry that there are great divagates between the lifetimes obtained from the experiment and the theory calculation results which only considering the radiative and Auger recombination processes. This difference is the evidence that the SRH mechanism can not be neglected. For example, the radiative and Auger lifetime of the HgCdTe for x = 0.231 are 1200 and 170 ns (shown in Fig.1a) respectively while the measurement lifetime is about 70 ns. Using Eq (2), the SRH lifetime is 130 ns. In this case, the effect of SRH and Auger process are the dominant mechanisms on carrier lifetime while the radiative process can be neglected. The lifetimes 510, 420 and 180 ns are radiative, Auger and SRH recombination respectively for x = 0.305; therefore, the only dominant recombination mechanism is SRH process. These results are consisted with the conclusion derived by Schacham [1] that the Auger process is more effective for low values while the SRH recombination are dominated for high compensated materials; The lifetimes 340, 6000 and 360 ns are radiative, Auger and SRH recombination respectively for x = 0.418, in this case, the radiative mechanism play more important role even can exceed the SRH process in the recombination process. For all samples, the SRH recombination has a full impact on minority carrier lifetime; therefore, it is an important recombination mechanism in minority carrier recombination process. In figure 4, our results also show that the carrier lifetime is in the range of 18 ~ 407 ns at liquid nitrogen temperature for the measured detectors of four compositions. With the composition increasing, the minority carrier lifetimes have an increasing tendency, and the lifetime of the short wavelength infrared detectors are the longest comparing to other detectors.

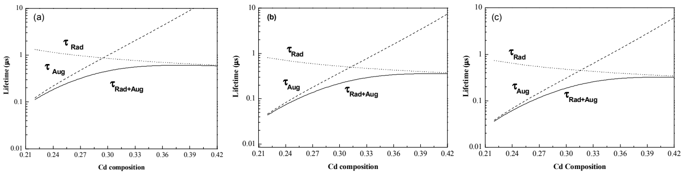

Fig 1The calculated minority carrier lifetime as a function of composition for *p*-type $Hg_{1-x}Cd_xTe$ with the different doping concentration. (a) 4.96×10^{15}cm^{-3} (b)8.08×10^{15}cm^{-3} (c)8.87×10^{15}cm^{-3}. The lifetimes were assumed to be determined by Auger and radiative recombination mechanisms. Also shown are the calculated Auger and radiative lifetimes for these carrier concentrations.

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