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Transient Response of Photoconductive Detectors under Laser Irradiation

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ABSTRACT

With photoconductive effect and heat effect in semiconductor detectors irradiated by high power laser taken into consideration, a new drift-diffusion model is put forward which based on the conventional model. Nonlinear coupled dynamic equations for photoconductive is established. The simulation calculation to photoconductive detectors was carried out by using appropriate differential method and designing programs capable of researching its photoelectric character.

Keywords: photoconductive detector; transient response; simulation calculation

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INTRODUCTION

Along with the development of photoelectron technology and optoelectronic countermeasure technology, people pay more attention to interaction between laser and photoelectric detector especially the effect of photoelectric detector on strong laser[1]. However, the current work is mostly concentrated on the measurement of damage threshold of various detectors and research on the mechanism of destruction. But in the middle power laser irradiation, Study on dynamic response of photoconductive detector is less, while the traditional model is only applicable for low power light irradiation, not applicable in the intensity range.

The paper establishes the theory model which describing the dynamic response of photoconductive semiconductor detectors to laser irradiation and nonlinear coupled dynamic equations. And the dynamic change of the output signal of the detector under laser irradiation is gotten. According to this model, it is necessary to take reasonable algorithm and corresponding calculation program to do analog computation of the PC detector. The dynamic change of the output signal of the detector under laser irradiation is obtained.

THE WORKING PRINCIPLE OF PHOTOCONDUCTIVE DETECTOR

Figure 1 shows the form of photoconductive detectors used most often work mode. The detector and the load resistor in series, and is connected with the DC bias voltage. For the low resistivity detector ($HgCdTe$ photoconductive detectors work in the 8~14 m wavelength range, typical resistance value is about 100）,which Often used in circuit of constant current mode. This time the load resistance R_L is much larger than the detector resistance R_D , the voltage of detectors (or load resistor voltage changes) as an output signal. In high resistivity detector, most use a constant voltage circuit which the change of current in the circuit is the output signal.

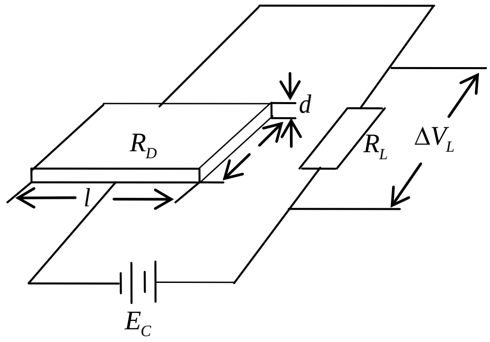

Fig.1The working principle graph of PC-type detector

When the detector uses constant current circuit model shown in Fig1 (($R_L >> R_D$)), optical voltage signal of detector output was:

$$\Delta V_L \approx \frac{\eta P_\lambda \lambda \tau_n}{hcnlwd} \cdot \frac{R_D}{R_L + R_D} V \approx \frac{\eta P_\lambda \lambda \tau_n}{\sigma hcn(wd)^2} \cdot \frac{V}{R_L} \qquad (1)$$

Among them $R_D = \frac{1}{\delta wd}$, l 、 w 、 d respectively for length, width and thickness of the detector, σ represents the conductivity. If detector is made of N type semiconductor, due to hole in addition to low density than electronic, the rate of migration is much lower than the electron, the contribution to the conductivity of the hole can be ignored, then the conductivity can be expressed as $\sigma = ne\mu_n$. n is the electron density, η is quantum efficiency, P_λ represents the light power density in wavelength of λ , h is Planck's constant, c is the speed of light, V is the bias voltage of R_D , τ_n 、 τ_p are the electron life and the hole life respectively.

ESTABLISH THE THEORETICAL MODEL

Because of the temperature change of material can affect equilibrium carrier and mobility, so when the semiconductor is irradiated by laser, it is necessary to consider the photoelectric effect and thermal effect. Traditional drift diffusion model can only apply to the low-power irradiation or low magnetic field, based on traditional model, the paper presents an improved theoretical model, the model is not only suitable for low-light irradiation but also suitable for high-light irradiation.

THE IMPROVED DRIFT DIFFUSION MODEL

If the incident light vertical radiation to the detector and the front is covered evenly, the physical quantity can be used as a one-dimensional model. By using a semiconductor material of the drift diffusion model, the equations of carrier concentration can be written when the laser irradiated semiconductor. Current density of electrons and holes are respectively can be expressed as:

$$\frac{\partial p}{\partial t} = G - R_p - \mu_p E \frac{\partial p}{\partial x} - \mu_p p \frac{\partial E}{\partial x} + D_p \frac{\partial^2 p}{\partial x^2} \quad (2)$$

$$\frac{\partial n}{\partial t} = G - R_n + \mu_n E \frac{\partial n}{\partial x} + \mu_n n \frac{\partial E}{\partial x} + D_n \frac{\partial^2 n}{\partial x^2} \quad (3)$$

n and p respectively represents electron density and hole density, $n = n_0 + \Delta n$ 、 $p = p_0 + \Delta p$, n_0 、 p_0 respectively represents thermal equilibrium electron density and hole density, Δn 、 Δp respectively represents photo-generated electrons density and photo-generated hole density. E represents the electric field intensity at the point of the carrier, D_p 、 D_n respectively represents electron diffusion coefficient and hole diffusion coefficient, $D_p = \mu_p kT/e$, $D_n = \mu_n kT/e$, μ_p 、 μ_n respectively represents electron mobility and hole mobility, k represents the Boltzmann constant. Because the photo-generated electrons and holes are produced in pairs,so their generation rate are equal, the G stand for them. If the incident light frequency is ν, power density is $P_\lambda(t)$, the quantum efficiency of holes electron pairs is η, reflection coefficient of the front surface of detector is r, the absorption coefficient of material is α, the generation rate of photo carrier is:

$$G(x,t) = \alpha\eta(1-r)P_\lambda(t)\exp(-\alpha x) / h\nu \quad (4)$$

R_n、R_p respectively represents electron recombination rate and holes recombination rate.

In the process of carrier transport, the total current density of detector is carrier current density and the displacement current density and, the dynamic equations of the electric field is:

$$\varepsilon\frac{\partial E}{\partial t} = J - e[\mu_p p + \mu_n n]E + eD_p\frac{\partial p}{\partial x} - eD_n\frac{\partial n}{\partial x} \quad (5)$$

When high-power laser irradiates photoconductive detectors, it not only produces photoconductive effect, but also produces heat effect, which shows increasing temperature. The equation (2), (3) and (5) implies the temperature, thus when irradiation light turn strong, the impact of temperature change need to be considered. Device operating at low temperature condition generally is encapsulated in the liquid nitrogen cooling Dewar, because of the Dewar is evacuated, the heat convection and heat radiation can be ignored. General radiation beams can completely cover the light receiving surface of the photoelectric detectors, the size of chip surface is much larger than the thickness, so it can the one-dimensional heat conduction model.

$$c\rho\frac{\partial T}{\partial t} = \kappa\frac{\partial^2 T}{\partial x^2} + \alpha(1-r)P_\lambda\exp(-\alpha x) + \frac{J^2}{ne\mu_n} \quad (6)$$

T represents temperature, c、ρ and κ respectively represents the heat capacity, density and thermal conductivity of material.

Chip resistor of detector for:

$$R_D = \frac{l}{\int_0^d e(n\mu_n + p\mu_p)wdx} \quad (7)$$

Because the external bias resistor is much larger than the detector resistance, detector can be considered constant current working conditions. Then the output voltage and resistance of detector has the same variation.

Equation(2), (3), (5), (6) and (7) constitute the dynamics equations which describe the carrier transport processes of photoconductive semiconductor detector and the response to the irradiation of laser dynamic. It is an nonlinear partial differential equations, it is difficult to obtain the analytic solution, but it was calculated by numerical simulation.

THE SIMULATION CALCULATION

The distribution of p、n、E in detector under different laser power density and the transient change of the output signal of the detector can be gotten through the numerical solution of the equations. In order to ensure the stability and convergence of the solution, equation（2)、(3)、(5)、(6）can be solved by using implicit difference format, in order to ensure the accuracy of two order discrete, the boundary conditions are treated by using the central difference method.

Because the PC type $HgCdTe$ detector is a kind of infrared detector which is very promising, we can change the $Hg_{(1-X)}Cd_XTe$ material component X to alter the spectral response range.

The intrinsic carrier density n_i and temperature T and the component X of $Hg_{(1-X)}Cd_X Te$ have the following relationship[2]

$$n_i = \frac{(1+3.25k_b T/E_g)\times 9.56(10^{14})E_g^{3/2}T^{3/2}}{1+1.9E_g^{3/4}\exp(E_g/2k_b T)} \quad (\text{cm}^{-3}) \qquad (10)$$

$k_b = 8.625\times 10^{-5} eV/K$, E_g is the width of the forbidden band.

$$E_g = -0.295 + 1.87\chi - 0.28\chi^2 + (6 - 14\chi + 3\chi^2)\times 10^{-4} T + 0.35\chi^4 \quad (\text{eV}) \qquad (11)$$

When temperature is between 77K and 300K, electron mobility can be expressed as[4]

$$\mu_n = 2.84\times 10^9 T^{-2.2} \quad (\text{cm}^2\text{V}^{-1}\text{s}^{-1}) \qquad (12)$$

THE RELATIONSHIP BETWEEN THE THERMAL EQUILIBRIUM CARRIER DENSITY AND TEMPERATURE

From the formula (10) can be seen, there is a relationship between the intrinsic carrier density and temperature, therefore there is a relationship between the heat balance carrier density and temperature, too. When component $\chi = 0.205$, $N_D = 8\times 10^{14} cm^{-3}$,the relationship between the thermal equilibrium electron density and temperature is obtained by the formula of（8)、(11)、(12）,as shown in Figure 2.

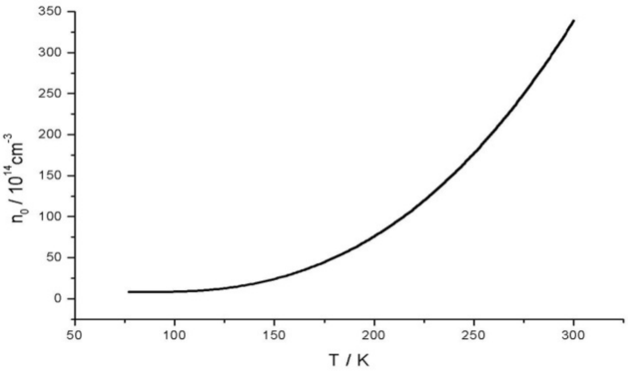

Fig.2 Heat equilibrium electron consistency change with

Temperature ($N_D = 8\times 10^{14} cm^{-3}$ **,** χ **=0.205)**

From the Fig2, we can see equilibrium carrier density is very small in low temperature (within 100K), $n_0 \approx N_D$, equilibrium carrier density and temperature basically have no relationship. When the temperature rises to 150K, equilibrium carrier density n_0 increase obviously with the increase of temperature T , and the equilibrium carrier density increased more quickly with higher temperature.

THE RELATIONSHIP BETWEEN ELECTRIC CONDUCTIVITY OF THE DETECTOR AND TEMPERATURE

Conductivity of the detector is:

$$\sigma_0 = e(n_0\mu_n + p_0\mu_p) \qquad (13)$$

From the effective mass of electron、hole are respectively [5] $m_n^* = 0.013m_e$, $m_p^* = 0.17m_e$,we can obtain

$\mu_p = 0.0765\mu_n$ .The relationship between conductivity and temperature is shown in Figure 3.

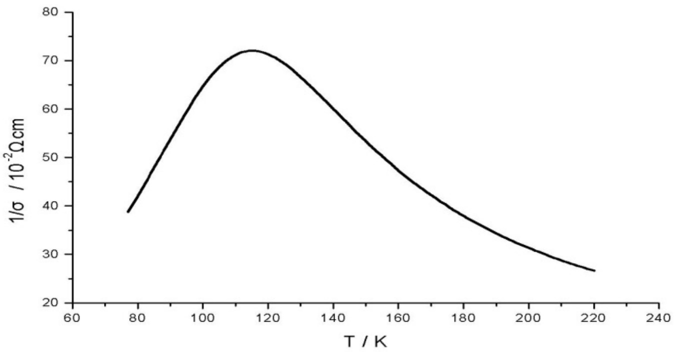

Fig.3 Electric conductivity of the detector vs temperature without light irradiation ($N_D = 8 \times 10^{14} cm^{-3}$ **,** χ **=0.205)**

The conductivity change without light irradiation of the detector has a maximum value, maximum, position linked to N_D and component X. When N_D =8×1014cm-3， χ =0.205, **Maximum** position at about 115K.

TRANSIENT BEHAVIOR OF THE DETECTOR RESISTANCE

The carrier density under laser irradiation reached the time required for a stable distribution is very short (microsecond), and detector temperature increases the time required for the millisecond, therefore it is considered that the temperature is constant in time less than 1 milliseconds. Solve the coupling equation (2), (3) , (5) and (6), to calculate the value of E 、 p 、 n .The calculated values of $p(x,t)$ 、 $n(x,t)$ feed into the discrete form of equation(6):

$$R_D = \begin{cases} \dfrac{1}{\sum_{i=1}^{m} e(n_i\mu_n + p_i\mu_p)w\,\Delta h} & 0 < t \le t_1 \\ \dfrac{1}{e[\mu_n n_0 + \mu_p p_0]wd} & t = 0, \quad t > t_1 \end{cases} \qquad (14)$$

The variation of $HgCdTe$ detector resistance under illumination was obtained, t_1 represents the illumination time。The calculation result of R_D with the illumination time under 1.06μm laser irradiation was shown in fig.4. The detector components $\chi = 0.205$, impurity concentration $N_D = 8 \times 10^{14} cm^{-3}$, $HgCdTe$ chip size is 1.25×0.25×0.015mm3.Through the simulation calculation, conductivity of the detector without light irradiation is 95.8Ω ,but the actual measured value is 98Ω , the error is due to the presence of contact and lead resistance.

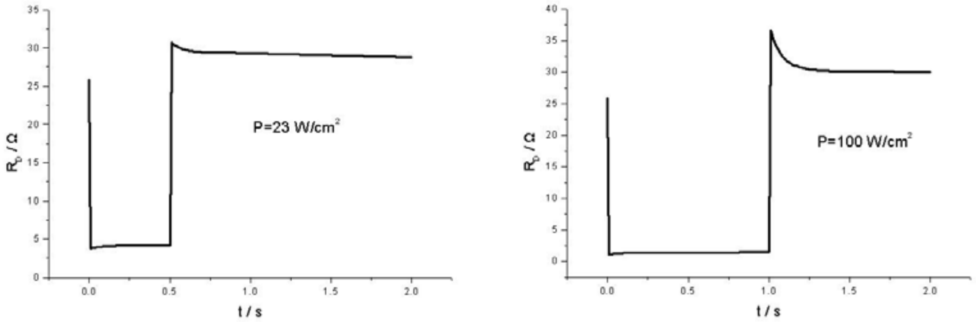

Fig.4 The imitative results of instantaneous change behaviors of electrical resistance of fig.4 The PC-type $HgCdTe$ **detector irradiated by 1.06 μ m laser**

The photoconductive effect of detector produces quickly under laser irradiation, the photon-generated carrier density is relatively large, so the resistance decreases quickly. When the laser stopped irradiation, the value of R_D did not immediately return to the value before laser irradiation, but up to a certain value, and then go into the slow decline phase. The result is caused by the thermal effect, during the laser irradiation, the detector temperature gradually increased by thermal effect, thus the resistance of detector without light irradiation increased.

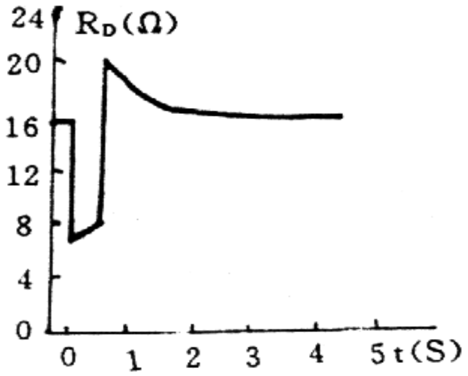

Fig.5 The experimental result of instantaneous change behaviors of electrical resistance of the PC-type $HgCdTe$ detector irradiated by 1.06 μ m laser

Figure 5 is the experimental results of PC type $HgCdTe$ detector resistance transient behavior under 1.06μm laser irradiation in document[3].The power density of laser is 23 W/cm2, irradiation time is 0.5 seconds. Figures 4 and figures 5 show that the transient behaviors of the detector are consistent with the law, but there are some differences in values, the differences relate to the parameters in the calculation, especially we do not know the true size of the detector used in the experiment, so the size of the detector is used in typical values in the calculation which have a great influence on the resistance value.

CONCLUSION

The paper establishes the transient response theoretical model of PC type semiconductor detectors irradiated by laser based on drift-diffusion theory of carrier. Compared with the traditional model, the model considers the density change of the heat balance carrier and the mobility change of carrier were caused by not only the photoconductive effect but also thermal effect. The model can successfully describe transient response of PC type semiconductor detector under the laser radiation. When the irradiation light power is weak, the temperature of detector changes little, then the result is the same as the traditional model, when the irradiation light power is very strong ,the detector temperature can be calculated, the detector can be judged whether the detector material is to be melted ,ablation ,etc according to the detector temperature. Therefore, the model has the universal significance.

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