광-마이크로파 기반 유도플라즈마의 과도응답 특성에 관한 연구

논 문
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Study of Transient Response in Non-uniform Plasma Layer with Optically-Controlled Microwave Pulses

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Abstract - In this paper we develop the characteristic of density on non-uniform plasma in different layer of the semiconductor with optically controlled microwave pulses. The transient response of the microwave pulses in different plasma layer has been evaluated by calculating the variation of the reflection function of dielectric microstrip lines. The lines has used under open-ended termination containing optically induced plasma region, which has illuminated a laser source. The characteristics impedances resulting from the presence of plasma are evaluated by the transmission line model. The analyzes the variation of transient response in a 0.01cm layer near the surface for frequency range from 1GHz to 128GHz. The diffusion length LD is larger than compared to the absorption depth $1/\alpha\iota$. The variation of characteristic response in plasma layer with microwave pulses which has in deferentially localized has been evaluated analytically.

Key Words : Non-uniform plasma, Semiconductor layer, Micro-strip lines, Transient response, Optically-controlled microwave pulses.

1. Introduction

The growing demand for signal processing at very high rates particularly with high capacity optical link applications in communications has enhanced the interest in micro-frequency band technology [1, 2]. The possibility of controlling the propagation characteristics of these waveguide with an optical beam from conventional semiconductor lasers may allow the construction of important active devices for signal manipulation such as filters, phase shifters, modulators, directional couplers and so on [3, 4].

When photons with energy higher than the band gap illuminates high resistivity semiconductors such as silicon and gallium arsenide, and solid-state plasma is induced in the semiconductor. The dielectric constant of the optically illuminated semiconductor takes the complex form at microwave and millimeter-wave frequencies, and this can be useful in the design of optically controlled wave phase shifters and attenuators [5]. The reflection and transmission of millimeter waves from optically induced plasma in a semiconductor were studied as a means of optically controlling of microwave in a quasi-optical system [6, 7].

In this study, we calculate the density of the induced carrier in different plasma layer. So the transient response in different layer plasma can be gotten. We analyze the semiconductor plasma characteristics in the dielectric microstrip line with optically induced plasma region by the way of calculating the variation of the reflection function. Then we have modeled the dielectric/plasma waveguide using a more accurate non-uniform dielectric profile characterizing the plasma created by an absorbed optical beam. The frequency used in the microstrip transmission line in this paper is from $1GHz$ to $128GHz$. The reflection characteristics are presented in the form of functions having frequency ω dependent variables.

We have modeled the dielectric/plasma waveguide in the non-uniform layer using the multipoint boundary-value routine COLSYS. The exponential plasma profile has been explored in detail because it is the form of the plasma density resulting from both the absorption of optical radiation and carrier diffusion. The exponential tail of free carriers extending into the waveguide continues to give a loss as the density increases because the fields can not be completely extinguished from the highly absorbing plasma region [8, 9].

2. Effects of Non-uniform Plasma Layer

When a semiconductor material is illuminated with laser photon energy greater than the band gap energy of

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the semiconductor, photons are absorbed, creating electron/hole pairs and resulting in a thin layer of plasma near the surface of the material. The power is absorbed as the light penetrates into the material, decreasing exponentially. As a result, the induced plasma density decreases approximately $exp(-a_i|x|)$ where a_i is the absorption coefficient of *GaAs* and x is the position along the penetration direction of the laser beam. The illumination is also considered to be non-uniform such that the variation along y (the waveguide width) is of the Gaussian type.

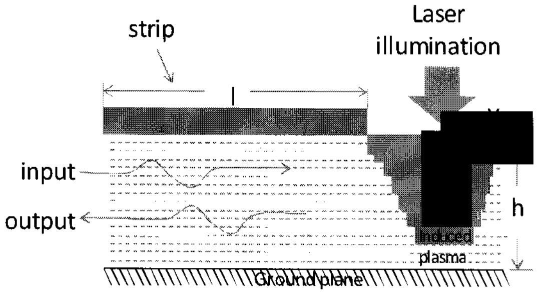

Fig. 1 The plasma layer in induced non-uniform density with an open-ended illuminated termination.

The presence of electron-hole plasma in the semi conductor produces of modification of the conductive as well as the dielectric properties of the semiconductor material [1, 7]. The dielectric constant in the plasma-induced layer semiconductor material can be analyzed by the equation of motion of charge carriers in the semiconductor considering the classical electron-hole plasma theory as predicted by the Drude-Lorentz equation [8, 9]. One end of the strip is connected to an input/output port and the other end is open-terminated as shown also in figure 1. The laser illumination induces electron-hole pairs in the semiconductor near the open end of the strip. The density of the induced carrier is assumed to be exponentially distributed from the surface to the interior.

The plasma region ΔZ is assumed to have a uniform density of free carriers. The relative permittivity of plasma induced in a semiconductor is given by [10]

$$\varepsilon_p = \varepsilon_s - \sum_{i=e,h} \frac{\omega_{pi}^2}{\omega^2 + \gamma_i^2}(1 + j\frac{\gamma_i}{\omega}) = \varepsilon_{pr} - j\varepsilon_{pi} \tag{1}$$

$$\omega_{pi}^2 = \frac{N_p \times q^2}{\varepsilon_o \times m^*} \quad (i=e,h) \tag{2}$$

where the subscripts and indicate the electron and hole and is the relative permittivity of materials. Also γ_i is collision frequency and γ_i is related to the relaxation time of the carrier τ_i, by $\gamma_i = 1/\tau_i$, ω_{pi} is the plasma angular frequency, q is the electron charge, m^* is the effective mass of the carrier, and N_p is the plasma density. The frequency and plasma dependence of the actual component of the dielectric constant is fairly weak, whereas the imaginary component of the dielectric constant shows a strong variation with frequency and density of plasma [9, 11].

3. Plasma Distribution Layer

The plasma generation due to laser illumination occurs in a region adjacent to the air/semiconductor interface. For photon energies of approximately E_{ph}=3.5eV the absorption coefficients of *GaAs* and *Si* are about $10^6 cm$. Consequently, the e^{-1} absorption depth for the light is about 0.01μm. In this section, we present a solution of the carrier diffusion equation in a semiconductor assuming the carriers are generated by an exponentially absorbed source. The carrier diffusion lengths are assumed to be much smaller than the waveguide width [9].

The analysis begins with the solution to the diffusion equation for excess carriers due to an incident laser beam of power P_o *watts/cm²* at the surface $x=0$. In steady state, the excess carriers $N(x)$ satisfy

$$L_D^2 \frac{d^2 N}{dx^2} - N = -\tau R(x)$$

$$R(x) = \frac{\eta \alpha_l}{h\gamma} P_o e^{-\alpha_l x} \tag{3}$$

where L_D is the carrier diffusion length, τ is the spontaneous carrier lifetime, and R is the pump due to the incident laser beam. Since the light injected into the semiconductor waveguide is attenuated, $R(x)$ is the position dependent pump rate. η is the internal efficiency, a_l is the light absorption coefficient, $h\gamma$ is the photon energy, and P_o is the light power at $x=0$.

If we assume $a_l L_D >> 1$ and $a_l L_D >> S\tau/L_D$ the result can be approximated as $N_x = N_o e^{-x/L}{}_D$. Therefore the carrier density at the surface is $N_o = \tau\eta P_o/h\gamma L_D(1+S\tau/L_D)$, where τ is the surface recombination velocity and S=$10^5 cm/s$ for unpassivated *Si* and *GaAs*. However, with a properly prepared *Si* surface, S can be much smaller [9, 12]. In Fig. 2 the density of the induced carrier has digressive from $8\text{x}10^{16} m^{-3}$ in different plasma layer.

On the other hand, if the diffusion length L_D is small compared to the absorption depth $1/a_l$, The excess carrier diffusion becomes $N_x = N_o e^{-x/Lo}$ where $N_o = \tau\eta P_o/h\gamma$. In Fig. 3 the density of the induced carrier has digressive from $8\text{x}10^{20} m^{-3}$ in different plasma layer.

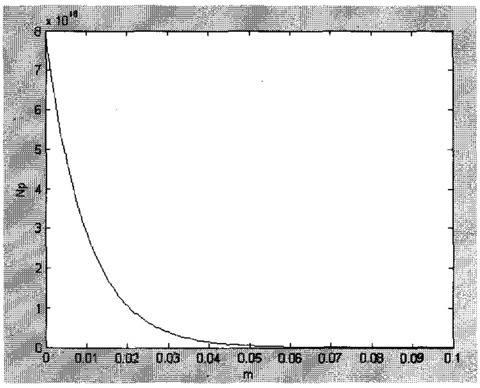

Fig. 2 The density of the induced carrier in plasma layer when αιLD>>1 and αιLD >>Sτ/LD.

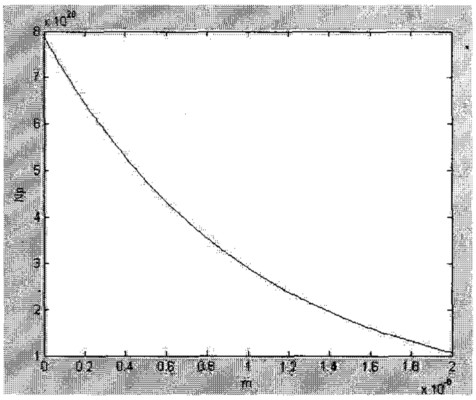

Fig. 3 The density of the induced carrier in different plasma layer when αιLD<<1.

In both of the limiting cases discussed above, the carrier density has an exponential dependence. Since the dielectric constant is proportional to the square of the plasma frequency, the corresponding dielectric constant will be proportional to the carrier density. So we can get the figure of the density of the plasma in the above different situation. And the first part data was used to analyze the transient response in different layer.

4. Proposed Transient Response in Layers

A transmission line, on the other hand, the capacitance and the conductance are also both taken into account. The reflection characteristics of this line are theoretically investigated with respect to the illuminating light using an equivalent circuit model [11].The variation in microstrip line based on optically controlled microwave pulses is shown in Fig. 4.

Supposing that the equivalent terminal impedance at the open end is represented as Z_L, then we can derive the $Z_L = R+1/j\omega C$ and a transmission line model can be also expressed as shown in Fig. 4 with Z_L and the characteristic impedance Z_o.By the transmission line equations, the input impedance Z_{IN} can be deduced from Z_L, Z_o and other parameters. Then the reflection wave function can be calculated by the circuit model through our suggested system, which has induced plasma with optically controlled pulses. In most microstrip configurations, transmission loss is neglected due to the compactness of an entire circuit. The total attenuation of the line is insignificant due to the short line length [13].

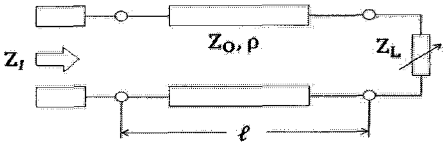

Fig. 4 Transmission line model of non-uniform plasma layer containing the equivalent terminal impedance

If the attenuation is primarily due to the dielectric loss, the dielectric constant ε becomes a complex quantity. In Maxwell's equation, we can $\varepsilon=\varepsilon_o\varepsilon_{pr}$ with the capacitance per unit length $C= \varepsilon*l/h$ and the resistance per unit length is $R = l/w*[\omega\mu/2\sigma]^{1/2}$, with l is the strip length and ω is the wide of the strip. Assuming input termination reflects some of energy originally sent down the line except for the completely matched condition. The Amplitude in time and frequency are calculated by Z_{IN} and the characteristics impedance of the transmission model.

The microwave signal is input to the port and the reflected signal is calculated through a directional coupler connected to the same port. The input microwave is almost totally reflected in the dark state, and increasing the frequency reduces amplitude of the reflection. The characteristics response for the pulse modulated signal, which is our equivalent model transient response with optically-controlled wave pulses based on microstrip lines, can be written by [14]

$$O(\omega) = \rho_{in}(\omega)e(\omega) \tag{4}$$

where $\rho_{in}(\omega)$ is dielectric variation in the plasma-induced layer and $e(\omega)$ is characteristics response in the frequency reflection variation.

5. Variation of Transient Response in Plasma Induced Layer

If we assume a_lL_D>>1 and a_lL_D >>$S\tau/L_D$, then the characteristic of variation in microstrip lines with optically controlled microwave pulse. In Fig. 5 the reflection of the input microwave was about $9\text{x}10^{-9}$ largest at the maximum density of the plasma in the surface of the semiconductor, as the density of the plasma increased below the reflection reduced and was closed to 0. The phase of the reflection of the microwave in the surface of the semiconductor is gotten. In Fig. 6 the maximum phase was about 3.8x10^{-10} in the depth of 0.075*m*. If the diffusion length L_D is small compared to the absorption depth $1/\alpha_L$, in Fig. 7 the reflection of the input microwave was about 2x10^{-10} largest at the maximum density of the plasma in the surface of the semiconductor, as the density of the plasma increased below the reflection reduced and was closed to 0. In Fig. 8 we can see that the maximum phase was about 2x10^{-10} in the depth of 1.6*μm*.

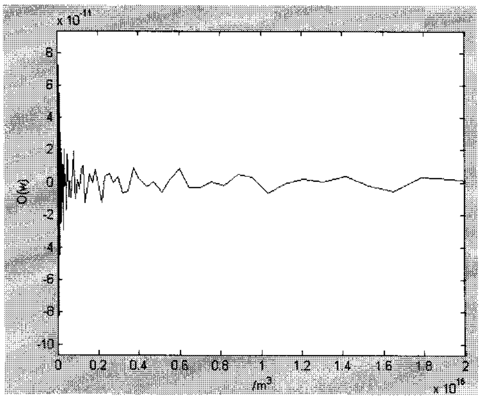

Fig. 5 The characteristic response in different density of the plasma layer when $\alpha_L L_D$>>1 and $\alpha_L L_D$ >>$S\tau/L_D$

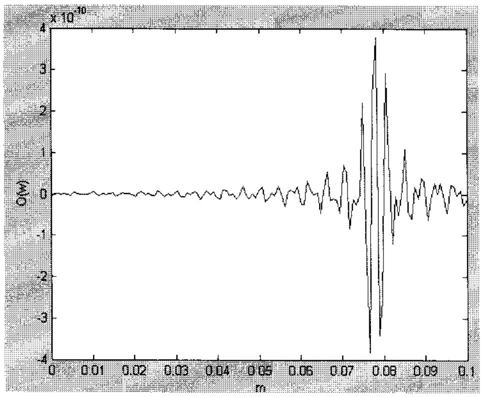

Fig. 6 The characteristic response in the different depth of plasma layer when $\alpha_L L_D$>>1 and $\alpha_L L_D$ >>$S\tau/L_D$.

The two relations couple the time and frequency dependent responses for liner microwave circuits in our equivalent model. First, we have considered the pulse-modulated sinusoid signal for input estimation, which has the amplitude modulating carrier shifts angular frequency ω to $(\omega-\omega_0)$ Our new proposed model with non-uniform plasma induced based by optically -controlled microwave pulse in [13, 14].

For the analysis in variation of transient-response in open-ended microstrip lines with optically-controlled microwave pulses, we have driven deferentially localized *O(w)* for variation response using by pulse-modulated sinusoid signal. By calculating the differential of the reflection wave function we can observe the phase change of the energy in the reflection wave directly. The localized variation of *O(w)* can be deduced with our transmission line model by

$$O'(\omega)=\frac{d(O(\omega))}{d\omega} \qquad (5)$$

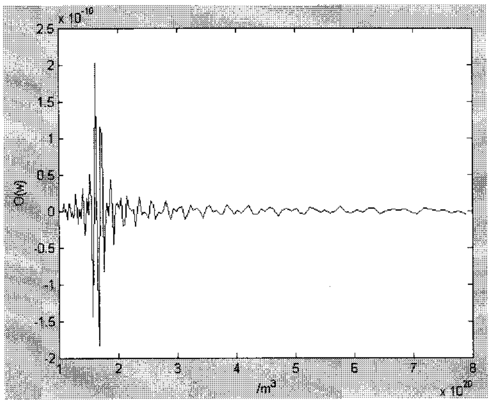

Fig. 7 The characteristic response in different density of the plasma when $\alpha_L L_D$<<1.

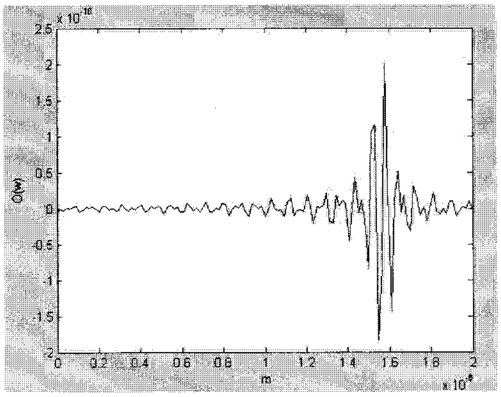

Fig. 8 The characteristic response in the different depth of plasma layer when $\alpha_L L_D$<<1.

The response of the variation of the reflection wave, which has pulse-modulated sinusoid signal, is shown in Fig. 9. The Fig. 9 depicts the response of the Fourier transform of the reflection wave and displays the characteristics of transiently responded signal in time pulse as a result of shift. The magnitudes are about 3.1, 2.8, 2.7 in the depth of 0.1*cm*, 0.01*cm* and 0.01x10^{-4}*cm* of plasma layer in time domain from 0.7*ns* to 0.86*nm* by shifted signal with variable constant when $a_L L_D$>>1. And in Fig. 10, the response of the Fourier transform of the differential variation of the reflection wave in optically controlled microwave pulses was showed. the average magnitudes are 4.7x10^{-9}, 4.4x10^{-9}, 4.2x10^{-9} in the depth of

0.1*cm*, 0.01*cm* and 0.0110^{-4}*cm* of plasma layer in time domain from 0.7*nm* to 0.86*ns* when $a_tL_D>>1$.

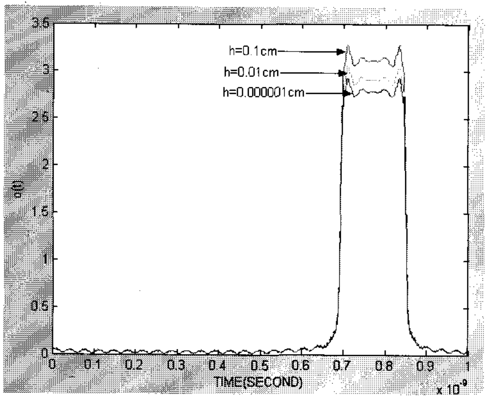

Fig. 9 Transient response in different depth of plasma layer in time domain by shifted signal with variable constant when $\alpha_t LD>>1$ and $\alpha_t LD >>S\tau/LD$.

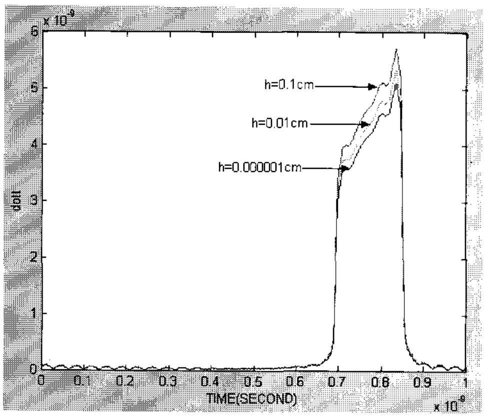

Fig. 10 The characteristic response in the different depth of plasma layers in deferentially localized when $\alpha_t LD>>1$ and $\alpha_t LD >>S\tau/LD$.

We give the wave that the dielectric materials were in normal run-time under our condition. If the actual measurement exceeds the limits, note that the site of the material is on abnormal state and needed for further measurement.

6. Conclusion

As the temperature and the input wave frequency changing, the reflection measurement of the open-ended microstrip lines which has a laser illuminated can be observed. Here we calculate the density of the induced carrier in different plasma layer. The reflection magnitude in the different layer of the non-uniform plasma can be gotten. The transient response in different density of the non-uniform plasma was shown in the figure. Here we give the result of the response in the depths of 0.1*cm*, 0.01*cm* and 0.01×10^{-4}*cm* near the surface for frequency range from 1*GHz* to 128*GHz* when $a_tL_D>>1$ and $a_tL_D >>S\tau/L_D$. By evaluating the variation of reflection $O(w)$, the change of the reflection amplitude are observed in the depth of 0.1*cm*, 0.01*cm* and 0.01×10^{-4}*cm*.

We also explain the characteristics of induced plasma layer with microwave pulses by changing the response signal. The amplitude modulating carrier frequency shifts 15GHz ~ 16*GHz* towards on modulated-response. Since our result has real-time response in induced non-uniform plasma layer, it can be used for decision defect or fault on semiconductor device and electrical circuit. And the best design of this system is that we can directly observe the phase of the reflected change in quantity.

Acknowledgements

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