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A Study of the Properties of Optically Induced Layers in Semiconductors Aided by the Reflection of Optically Controlled Microwave Pulses

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We present a study on the reflection of optically controlled microwave pulses from non uniform plasma layers in semiconductors. The transient response of the microwave pulses in different plasma layers has been evaluated by means of the reflection function of dielectric microstrip lines. The lines were used with an open-ended termination containing an optically induced plasma region, which was illuminated by a light source. The reflection characteristics impedance resulting from the presence of plasma is evaluated by means of the equivalent transmission line model. We have analyzed the variation of the transient response in a 0.01 *cm* layer with a surface frequency in the region of 128 *GHz*. In the reflection the variation of the diffusion length L_D is large compared with the absorption depth $1/\alpha_i$. The variation of the characteristic response of the plasma layer with differentially localized pulses has been evaluated analytically. The change of the reflection amplitude has been observed at depths of 0.1 *cm*, 0.01 *cm* and $0.1\text{x}10^{-5}$ *cm* respectively.

Keywords: Non-uniform plasma, Semiconductor layer, Micro-strip lines, Transient response, Optically controlled microwave

1. INTRODUCTION

Recently there has been increasing interest in the application of light-wave technology for the control, generation and measurement of microwaves. When photons with energy higher than the band gap illuminate high resistivity semiconductors such as silicon (*Si*) and gallium arsenide (*GaAs*), solid-state plasma is induced in the semiconductor. The dielectric constant of the optically illuminated semiconductor takes a complex form at microwave and millimeter-wave frequencies, and this can be useful in the design of optically controlled wave phase shifters and attenuators etc[1,2]. The considerable interest in the optical control of microwave is due to the potential use of new microwave devices in high-speeding signal processing, antenna beam scanning, phase shifters, modulators and optical switches[3,4].

The reflection from and transmission of millimeter waves through optically induced plasmas in a semiconductor were studied as a means of optically controlling microwaves in a quasi-optical system[5,6]. A high-intensity illumination system made of transient plasma structures can be utilized to circumvent the ubiquitous optical damage problem since the structures are already fully ionized[7].

In this study, we analyze the behavior of semiconductor plasmas in a dielectric microstrip line having an optically induced plasma region by calculating the dependence of the reflection function of the line on the plasma properties. 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 1 *GHz* to 128 *GHz*. 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 takes 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 plasma 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 the semiconductor, photons are absorbed creating electron-hole pairs which form a thin layer of plasma near the surface of the material. The induced plasma density decreases approximately as $exp(-\alpha_i|x|)$ where α_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.

The presence of an electron-hole plasmas in the semiconductor produces a 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 from 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 has an open-termination as shown also in Fig. 1. The

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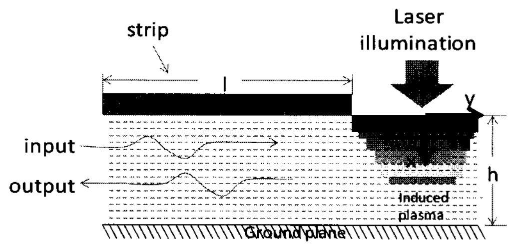

Fig. 1. The plasma layer of non-uniform density induced by laser illumination with an open-ended illuminated termination.

laser illumination induces electron-hole pairs in the semiconductor near the open end of the strip. The density of the induced carrier is assumed vary exponentially moving inwards from the surface.

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

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

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

where the subscripts $(i=e,h)$ refer to electrons and holes respectively. 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 plasma density[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}=3.5 *eV* the absorption coefficients of *GaAs* and Si are about 10^6. Consequently, the e^{-1} absorption depth for the light is about 0.01 *μm*. In this section, we present a solution of the carrier diffusion equation in a semiconductor assuming that 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/cm*^{2} at the surface $x=0$. In the steady state, the excess carriers $N(x)$ satisfy the equations

$$L_D^2 \frac{d^2N}{dx^2} - N = -\tau R(x)$$
$$R(x) = \frac{\eta\alpha_l}{h\gamma} P_o e^{-\alpha_l x} \qquad (3)$$

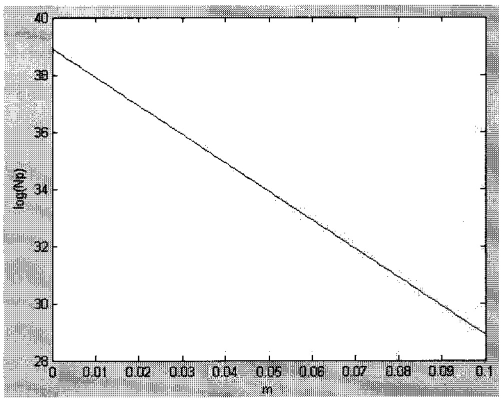

Fig. 2. The density of the induced carrier in plasma layers with $\alpha_t L_D >> 1$ and $\alpha_t L_D >> S\tau/L_D$.

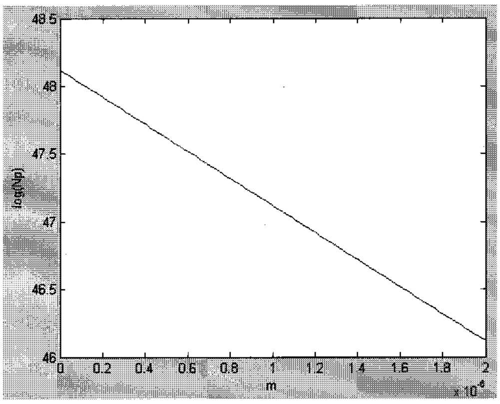

Fig. 3. The density of the induced carrier in different plasma layers with $\alpha_t L_D << 1$.

where L_D is the carrier diffusion length τ is the spontaneous carrier lifetime, and R is the generation rate 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, α_t is the light absorption coefficient, $h\gamma$ is the photon energy, and P_o is the light power at $x=0$.

If we assume $\alpha_t L_D >> 1$ and $\alpha_t L_D >> S\tau/L_D$ 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 changes by more than 38.5 *dB* in different plasma layer on a logarithmic scale.

If the diffusion length L_D is small compared to the absorption depth $1/\alpha_t$, then the excess carrier diffusion becomes $N_x = N_o e^{-x/L_o}$ where $N_o = \tau\eta P_o/h\gamma$. In Fig. 3 the density of the induced carrier varies by 48.1*dB* in different plasma layers. 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 evaluate the density of the plasma in the above different situation, which has optically induced layer in Semiconductor.

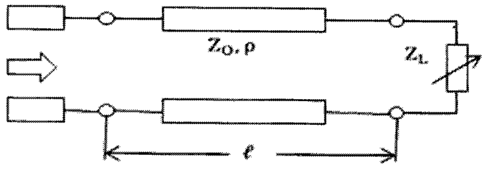

Fig. 4. Transmission line model of non-uniform plasma layer containing the equivalent terminal impedance.

4. PROPOSED TRANSIENT RESPONSE IN LAYERS

The capacitance and the conductance are also both taken into account in our equivalent transmission line model for analyzing with optically controlled waves. 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 with our equivalent model 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 the transmission line model can be also expressed as shown in Fig. 4 with Z_L and the characteristic impedance Z_o. Through 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 means of the transmission line model through our suggested system, which has plasma induced by optically controlled pulses. In the most microstrip configurations, transmission loss is neglected due to the compactness of the entire circuit. The total attenuation of the line is insignificant due to the short line length[13].

If the attenuation is primarily due to the dielectric loss, the dielectric constant ε becomes a complex quantity. In the Maxwell's equation, we can write $\varepsilon=\varepsilon_o\varepsilon_{pr}$ with the carrier density and capacitance per unit length $C= \varepsilon{*}l/h$ and the resistance per unit length is $R = l/\omega{*}[\omega\mu/2\sigma]^{1/2}$, where l is the strip length and ω is the wide of the strip. Assuming that the 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 from Z_{IN} and the characteristics impedance of the transmission model.

The microwave signal is fed into the port and the reflected signal is calculated through a directional coupler connected to the same port with optically controlled waves. The input microwave is almost totally reflected in the dark state, and increasing the frequency reduces the amplitude of the reflection. The characteristic 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 the dielectric variation in the plasma-induced layer and $e(w)$ is the characteristic response in the frequency reflection variation. The properties of optically induced layers in semiconductors based on reflection of optically controlled microwave pulses have evaluated.

5. VARIATION OF THE TRANSIENT RESPONSE IN PLASMA INDUCED LAYER

In analyzing with $\alpha_t L_D$>>1 and $\alpha_t L_D$ >>$S\tau/L_D$, the transient variations in microstrip lines with optically controlled microwave pulse has shown in Fig. 5. The reflection of the input wave was about -24 *dB*. The plasma density was a maximum value at the surface of the semiconductor and moving towards from the surface it drops rapidly to -26 *dB*.

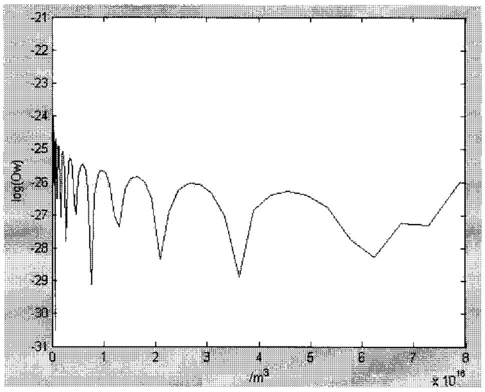

Fig. 5. The characteristic response as a function of the density of the plasma layer when $\alpha_t L_D$>>1 and $\alpha_t L_D$ >>$S\tau/L_D$.

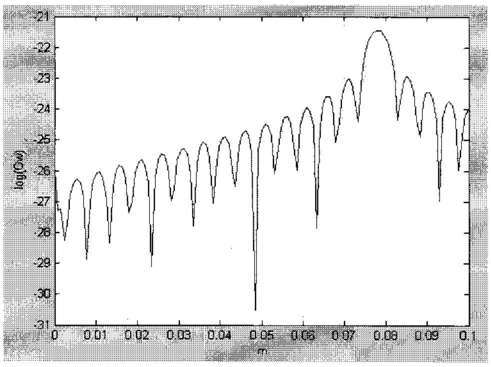

Fig. 6. The characteristic response in the different depth of plasma layer when $\alpha_t L_D$>>1 and $\alpha_t L_D$ >>$S\tau/L_D$.

The phase of the reflection of the microwave in the surface of the semiconductor is given in Fig. 6. The maximum phase was about -22.5 *dB* and it occurred at a depth of 0.075 *m*. If the diffusion length L_D is small compared to the absorption depth $1/\alpha_t$, the maximum in the reflection of the input microwave was about -23.7 *dB*. It occurred that the density of the plasma in the surface of the semiconductor was a maximum as the density of the plasma increased below the reflection reduced. The maximum phase was about -23.7 *dB* at the depth of 1.55 *μm* as shown in Fig. 8.

The two relation couple with time and frequency dependents on liner microwave circuits with our equivalent model. We have considered the pulse-modulated sinusoid signal for input estimation. The angular frequency of the amplitude modulated carrier shifts to angular frequency ω to $(\omega-\omega_o)$. Our proposed model has also involves the transient response function with optically controlled pulses[13,14]. In the variation of as a function of transient-response in open-ended microstrip lines, which has optically induced layers in semiconductors, we have derived a differentially localized function *O(w)* to define the transient response using a pulse-modulated sinusoid signal.

Evaluating 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 from relation with optically induced layers in semiconductors.

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

The response of the variation of the reflection wave, which has the form of a pulse-modulated sinusoid signal, is shown in Fig. 9. In Fig 10 we depict the response of the Fourier transform of the reflection wave at depths of 0.1 *cm*, 0.01 *cm* and $0.01\text{x}10^{-4}$ *cm* in the plasma layer and the characteristics of the corresponding transient response. The magnitude is largest at a depth of 0.1 *cm* and the least in a depth of $0.01\text{x}10^{-4}$ *cm*. In Fig. 10 the magnitudes differ only slightly at depths of 0.1 *cm*, 0.01 *cm* and $0.01\text{x}1^{-4}$ *cm* in the plasma layer and the largest magnitude is about 1 *dB*.

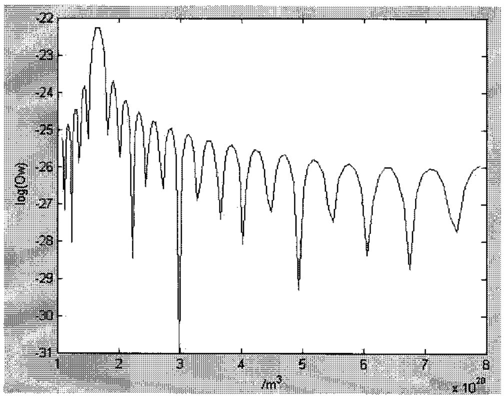

Fig. 7. The characteristic response as a function of density of the plasma, when $\alpha_t L_D$<<1.

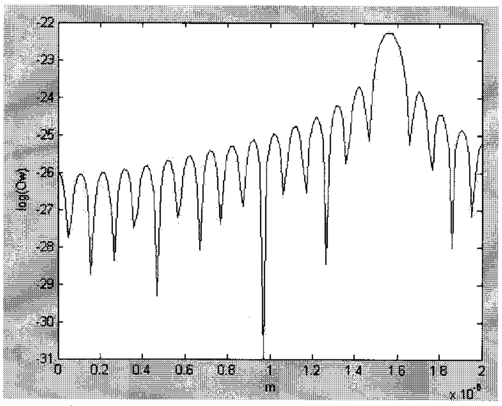

Fig. 8. The characteristic response in the different depth of plasma layer when $\alpha_t L_D$<<1.

The variation from 0.7 *ns* to 0.86 *ns* has been shifted when $\alpha_t L_D$>>1. The response of differential variation in the reflection wave with optically induced layer is shown in Fig. 11. The magnitudes vary from -20.5 *dB* to -19 *dB* at depth of 0.1 *cm*, 0.01 *cm* and $0.1\text{x}10^{-5}$ *cm* in the induced plasma layer, equivalent to 0.67 *ns* to 0.86 *ns* in the time domain when $\alpha_t L_D$>>1.

The variation of optically induced layers in semiconductors has evaluated as a function of time and frequency.

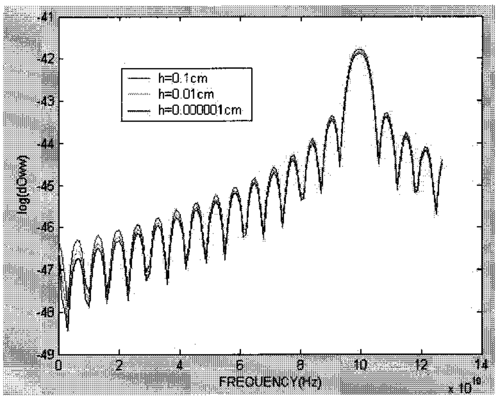

Fig. 9. Transient response at different depths in the plasma layer with $\alpha_t L_D$>>1 and $\alpha_t L_D$ >>Sτ/L_D.

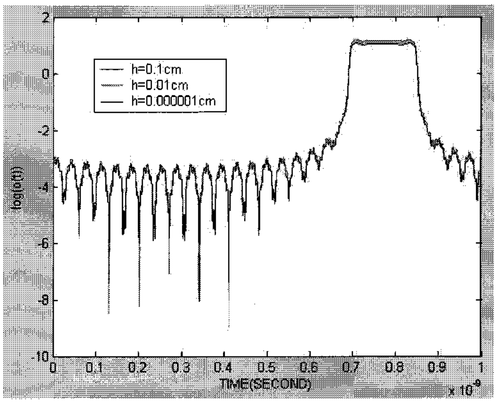

Fig. 10. Transient response at different depths of plasma layer with $\alpha_t L_D$>>1 and $\alpha_t L_D$ >>Sτ/L_D.

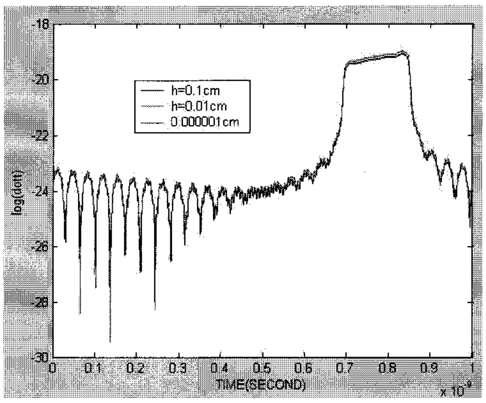

Fig. 11. The characteristic response in the different depth of plasma layer in differentially localized when $\alpha_t L_D$>>1 and $\alpha_t L_D$ >>Sτ/L_D.

6. CONCLUSIONS

Reflection and transmittance measurement with an optically controlled microwave pulses in the open-ended microstrip lines, which has a laser illuminated can be observed. We studied the properties of optically induced layers in semiconductors aided by the reflection of optically controlled microwave pulses. The transient response in different densities in the non-uniform plasma was also evaluated. We give the results for the response at depths of 0.1 *cm*, 0.01 *cm* and $0.1\text{x}10^{-5}$ *cm* in the plasma for the frequency range to 128 *GHz* with $\alpha_t L_D >> 1$ and $\alpha_t L_D >> S\tau/L_D$. The change in the reflection amplitude has been observed at depth of 0.1 *cm*, 0.01 *cm* and $0.1\text{x}10^{-5}$ respectively.

We have studied analytically the reflection and transmission characteristics of the plasma-induced layer with microwave pulses by changing the response signal. The amplitude modulating carrier frequency shifts to 14.15 *GHz* towards on modulated-response. The result demonstrates the real-time response of an optically induced non-uniform plasma layer. This response can be used to help with decision making concerning defects or faults in semiconductor devices and electrical circuits.

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