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Optically Controlled n-InP Distributed Phase Shifter

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ABSTRACT

The space charge modes in an n-InP diode with a suitably designed Schottky barrier cathode under illumination have been investigated numerically. It has been found that the cathode trapped domain mode changes into a travelling dipole domain mode with increasing illumination. An optically controlled phase shifter can be achieved by inserting an n-InP diode with a Schottky barrier cathode between a resonant microstrip lines in place of a conventional dielectric material. Phase shifts have been predicted as high as 2π radians/cm with the plasma density less than $10^{15}/cm^3$. The device has a gain as a result of the electron transfer from the lower valley with light mass to the upper valleys with heavy mass. Ultra-fast and high-repetition rate phase modulation is possible, since the life time of the excess carriers in an n-InP diode is less than 100 ps.

I Introduction

Recently, we have reported [1] that an n-GaAs diode with a suitably designed Schottky barrier cathode can be used as an electronically tunable distributed oscillator. The device can be achieved by inserting an n-GaAs diode with a Schottky barrier cathode between a resonant microstrip lines in place of conventional dielectric materials. The phase constant of the waves travelling in the oscillator is controlled by the length of the depletion layer in the diode, which in turn is controlled by the applied voltage.

The phase constant of the waves in the device can be varied by illuminating the semi-transparent metal cathode with above-bandgap radiation. Phase shifting is a foundmental control operation. One well-known method of alterling the dispersion of microwaves is to control the capacitance in p-i-n diode by electronically or optically. It should be, however, noted that large phase shifts have not been achieved [2] and there are large losses in p-i-n diode [3].

Vaucher et al. have analyzed in detail the steady-state millimeter-wave propagation characteristics of pure-Si and Cr-doped semi-insulating GaAs dielectric wave guide that contains a plasma-dominated region and predicted that phase shifts as high as $1400^{\circ}/cm$ can be achieved for modes operating near cutoff[4]. They have measured the millimeter-

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wave switching characteristics by optically generated plasma in Si [5,6] experimentally and demonstrated that wide bandwidth, high-repetition rate opto-electronic modulation of millimeter-wave is possible in Cr-doped semi-insulating GaAs material [7]. This method can be the future useful technology in the field of ultra-fast switching and gating of millimeter-wave signal. In their method, high plasma density, exceeding $10^{18}/cm^3$, is required for achieving a large phase shift with little attenuation of waves. In this paper, we propose a new method of phase shifting, that of optically controlled n-InP distributed phase shifter with a suitably designed Schottky barrier cathode contact. Phase shifts of 2π radians/cm are predicted for a plasma density less than $10^{15}/cm^3$, three orders of magnitude less than the plasma density required for the phase shifter proposed by Vaucher et al.[4]. This prediction is important, since we need a relatively low power laser source for controlling the phase shift of the device. In n-InP, in contrast to n-GaAs, electron-hole pairs recombine rapidly, i. e., in less than 100 ps, thus, high-speed and high-repetition rate phase shifting is possible. Furthermore, this n-InP distributed phase shifter exhibits a gain as a result of the electron transfer from the lower valley with light mass to the upper valleys with heavy mass. Hence, we investigate the operation characteristics of the device theoretically in this paper.

II Method

Recently, we have reported that the space charge modes in an n-GaAs diode can be controlled by interposing a thin highly doped layer between a metal and the active layer of an n-GaAs diode and by suitably designing the thickness of the highly doped layer [1].

The Schottky barrier height of a contact to n-InP diode is 0.4—0.5 eV, which is 0.3—0.4 eV lower than that to n-GaAs. Furthermore, the life time of hole-electron pairs in n-InP is less than 100 ps, which is several orders of magnitude less than that in n-GaAs, that is, high-speed and high repetion rate operation of a microwave modulator can be achieved in an n-InP diode. This is the reason why we choose an n-InP material for the present study.

As mentioned elsewhere [1], the effective Schottky barrier height can be controlled by interposing a highly doped layer between a metal and the active layer of an n-GaAs diode. The tunneling current traversing from the metal to the semiconductor can be controlled by varying the width of the potential barrier for electrons, which in turn is controlled by the width of the highly doped layer. The potential berrier narrows as the width of the highly doped layer increases, thus, the tunneling current traversing from the metal to the semiconductor increases with increasing width of the highly doped layer. This is the main reason why the effective Schottky barrier height decreases as the width of the highly doped layer increases.

Fig.1 shows the reverse saturation current versus cathode field as a function of the width of the highly doped layer, where the doping density of the highly doped layer is assumed to be $5\times10^{18}/cm^3$.

The operation of an n-InP transferred electron device with a Schottky barrier cathode contact can be simulated by using the results obtained above. As mentioned in the

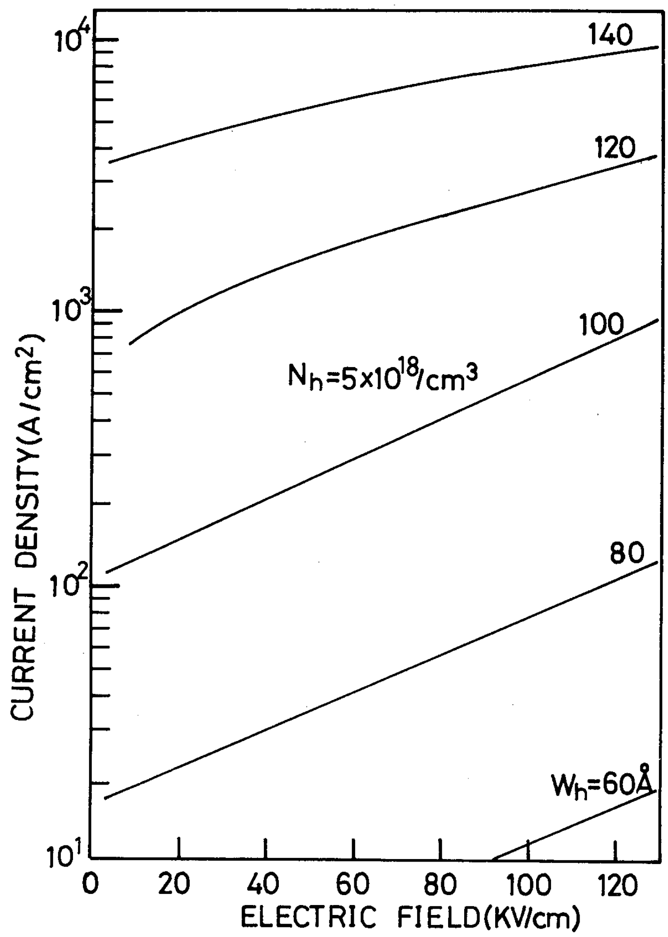

Fig.1 Saturation current versus Ed for various thicknesses of the highly doped layer.

previous paper [1], the travelling dipole domain mode changes into the cathode trapped domain mode with decreasing current traversing from the metal to the semiconductor. The diode operating in the cathode trapped domain mode shows a negative conductance over a fairly wide frequency range. The susceptance of the diode can be varied electronically. By illuminating the semi-transparent Schottky metal with above-bandgap radiation, plasma can be created in the depletion layer of the diode. Holes in the depletion layer are swept out immediately toward the cathode by the high electric field in the depletion layer. Electrons created in the depletion layer travel across the active gap toward the anode. The electron and hole dynamics are described by the following five equations.

$$\frac{\partial n}{\partial t} = -\frac{\partial J_n}{\partial x} + G - R \tag{1}$$

$$\frac{\partial p}{\partial t} = -\frac{\partial J_p}{\partial x} + G - R \tag{2}$$

$$J_n = nv_n - \frac{\partial D_n n}{\partial x} \tag{3}$$

$$J_p = pv_p + \frac{\partial D_p p}{\partial x} \tag{4}$$

$$\frac{\partial E}{\partial x} = -\frac{e}{\varepsilon}(n - n_D - p) \tag{5}$$

where n is the electron density, p is the hole density, J_n is the particle flow of electrons, J_p is the particle flow of holes, v_n is the electron velocity, v_p is the hole velocity, D_n is the elctron diffusion constant, D_p is the hole diffusion constant, n_D is the ionized donor density, G is the generation rate of hole-electron pairs, and R is defined by

$$R = \frac{p}{\tau_p} \tag{6}$$

where τ_p is the life time of holes.

Fig.2 shows the electric field versus distance for a donor density of $2\times10^{15}/cm^3$, where an applied voltage of 22 and a life time of 30 ps were assumed. As is clear in the figure, the width of the depletion layer increases as the intensity of illumination increases, which in turn the capacitance of the diode decreases with increasing intensity of illumination. For a higher generation rate of hole-electron pairs, the cathode trapped domain mode changes into the travelling dipole domain mode. The nature of optically triggered dipole domain can be successfully used for achieving an ultra-fast photo detector.

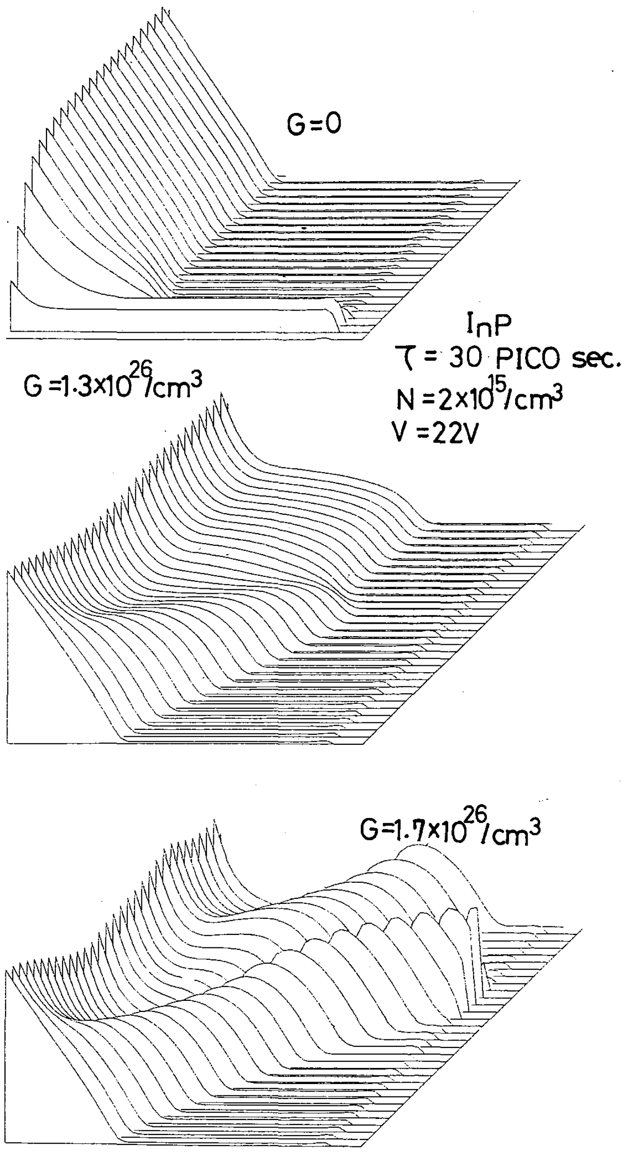

Fig.2 Field distribution in the n-InP diode with a Schottky barrier cathode. The cathode trapped domain mode changes into the travelling dipole domain mode as the intensity of illumination increases.

In this analysis, we have neglected the presence of the deep levels in the forbidden energy band. Charging and discharging rates of the deep levels are much longer than the time scale considered in the present paper, thus, the electron and hole dynamics are not influenced by the deep levels in the forbidden band.

III Analysis of an n-InP Distributed Phase Shifter with Schottky Barrier Cathode

In the preceding section, we have shown that the space charge mode in an n-InP diode with Schottky barrier cathode can be controlled by illuminating the semi-transparent Schottky metal with above-bandgap radiation. In this section, we shall investigate the time response of various physical quantities such as the electron density, elctric field etc., for small sinusoidal ac voltage. In order to calculate the two terminal admittance of an n-InP diode, a small ac voltage is superimposed on the dc voltage, and then applied to the diode terminal ; and finaly, the resulting current are expanded into the Fourier series. The admittance can be calculated from the expansion coefficients.

$$V(t) = V_d + V_a \sin(\omega t) \tag{7}$$

$$J(t) = \frac{q}{l}\int_0^l \{n(x,t) - \frac{\partial}{\partial x} D_n n(x,t) + p(x,t) v_p(x,t) + \frac{\partial}{\partial x} D_p p(x,t)\} dx + \frac{\omega V_a}{l}\cos(\omega t) \tag{8}$$

$$a_n = \frac{2}{T}\int_0^T J(t)\sin(\omega t)\,dt \tag{9}$$

$$b_n = \frac{2}{T}\int_0^T J(t)\cos(\omega t)\,dt \tag{10}$$

where V(t) is the terminal ac voltage, V_d is the dc voltage , V_a is the small ac voltage superimposed on the V_d, ω is the angular frequency, l is the diode length, and J(t) is the total current density. The two-terminal conductance G and susceptance S can be expressed as

$$G = \frac{a_1}{V_a}, \quad S = \frac{b_1}{V_a} \tag{11}$$

Fig.3 shows conductance and susceptance as a function of frequency, where a life time of hole-electron pairs of 30 ps, a donor density of $2\times10^{15}/cm^3$, and an applied voltage of 22 were assumed, respectively. Without illumination the n-InP diode do not exhibits a negative conductance. It should be noted that the diode exhibits a negative conductance for higher injection current.

The high field region exhibits a negative conductance as a result of the electron transfer from the lower valley with light mass to the upper valleys with heavy mass. The magnitude of negative conductance in the high field layer increases with increasing the electron density in the high field layer. The low-field region acts as a register. The diode terminal resistance is the sum of the negative resistance in the high field layer plus the positive resistance in the low field layer [8]. Thus, a positive diode terminal conductance changes into a negative conductance as electrons in the high field layer increases. Thus, a positive resistance changes into a negative resistance as the intensity

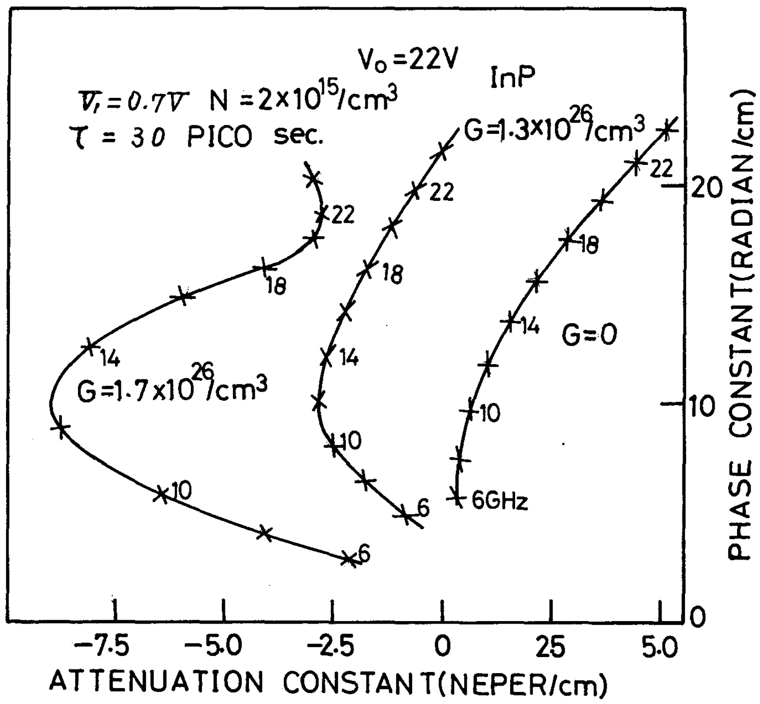

Fig.3 Admittance as a function of the intensity of illumination.

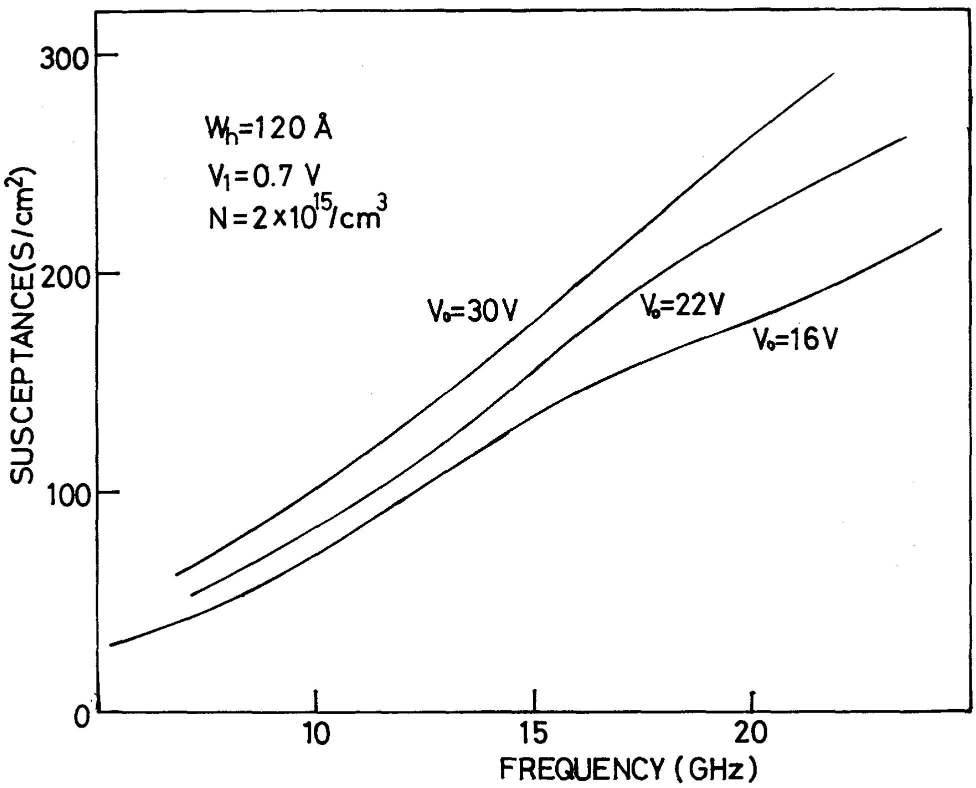

Fig.4 Susceptance as a function of the intensity of illumination. Susceptance reduces significantly with increasing illumination.

of illumination increases. Susceptance of the diode decreases rapidly as the intensity of illumination increases as shown in Fig.4. Photo-excited electrons widen the width of the partially depleted high field layer, thus, the susceptance of the diode decreases as the photo-excited electrons increases.

Next, we shall calculated the propagation constant of a microstrip line, into which an n-InP diode with suitably designed Schottky barrier cathode, as analyzed just above, is inserted in place of the conventional dielectric materials. As mentioned previously [1], the direction of a carrier drifting in the semiconductor is normal to the stripline, so that the semi-transparent Schottky electrode at the cathode and the ohmic contact at the anode can be used as the conductors of the microstrip line. Assuming that the electric field has an X component only, the wave propagates along the Z axis, and the electric field does not vary along the Y axis, Maxwell's wave equations reduce as

$$\frac{\partial^2 E_x}{\partial Z^2} = \mu \frac{\partial \tilde{K}}{\partial t} \qquad (12)$$

where $\tilde{K}$ is the total current density flowing in the diode. Substituting $j\omega$ in place of $\frac{\partial}{\partial t}$ into (12) and integrating it over x, we obtain the following differential equation.

$$\frac{\partial^2 \tilde{V}(z,\omega)}{\partial Z^2} = j\omega\mu l \tilde{Y}(\omega)\tilde{V}(z,\omega) \qquad (13)$$

where $\tilde{V}(Z,\omega)$ is the voltage across the line, $\tilde{Y}(\omega)$ is the admittance of the diode, μ is the permeability, and l is the diode length across the line. The solution can be expressed as

$$\tilde{V}(z,\omega) = C_1 e^{-kz} + C_2 e^{kz} \qquad (14)$$

where the propagation constant k is given by

$$k = \sqrt{j\omega\mu l \tilde{Y}(\omega)}$$

The real and the imaginary parts of k are the attenuation costant and the phase constant, respectively.

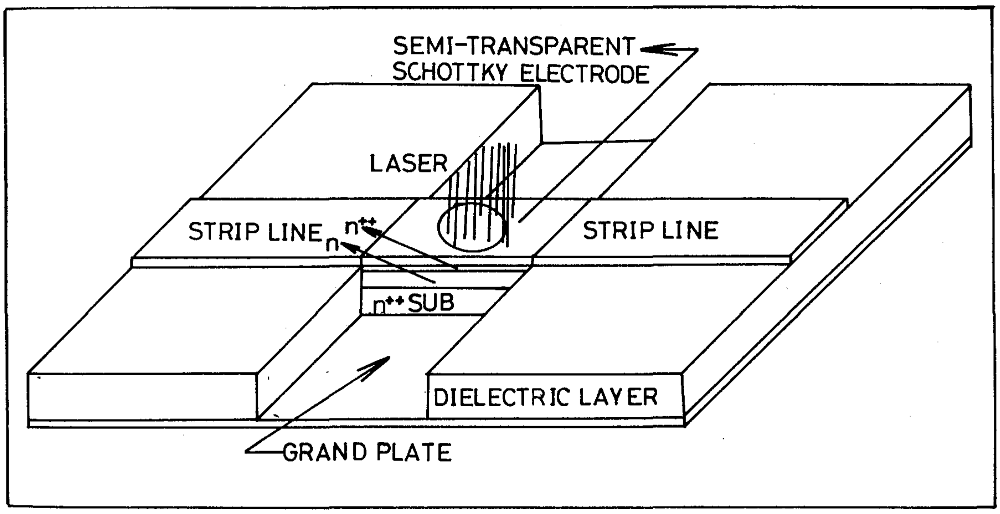

Fig.5 Structure of phase shifter. An n-InP diode with a Schottky barrier cathode is inserted into microstrip line in place of conventional dielectric material.

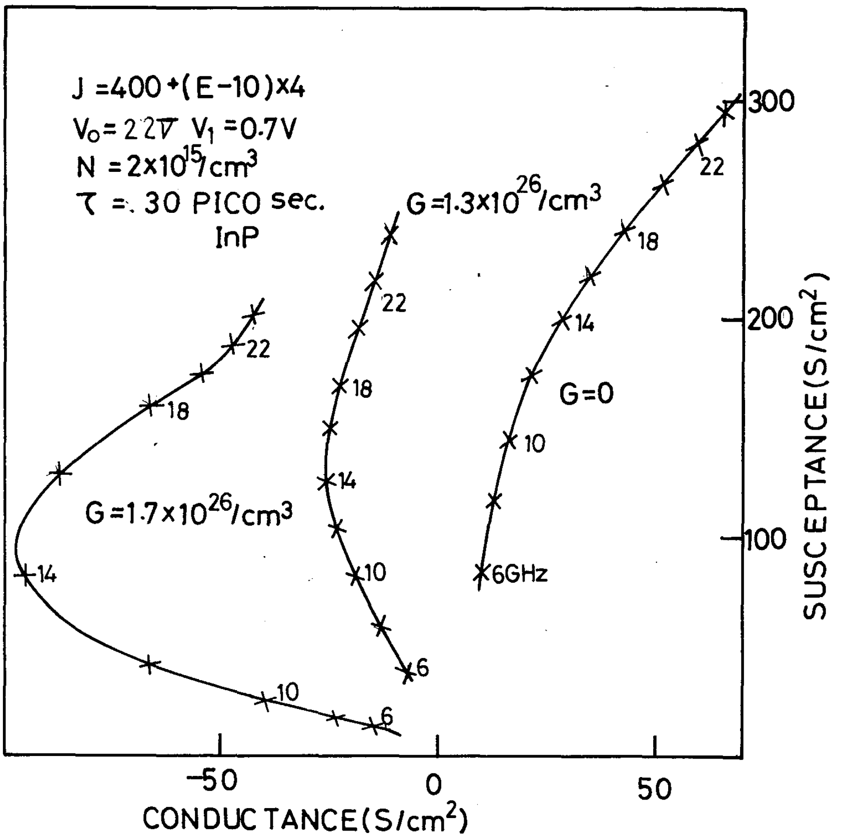

Fig.6 Propagation constant calculated from the results shown in Fig.3. A negative value of attenuation constant means that the wave grows with distance.

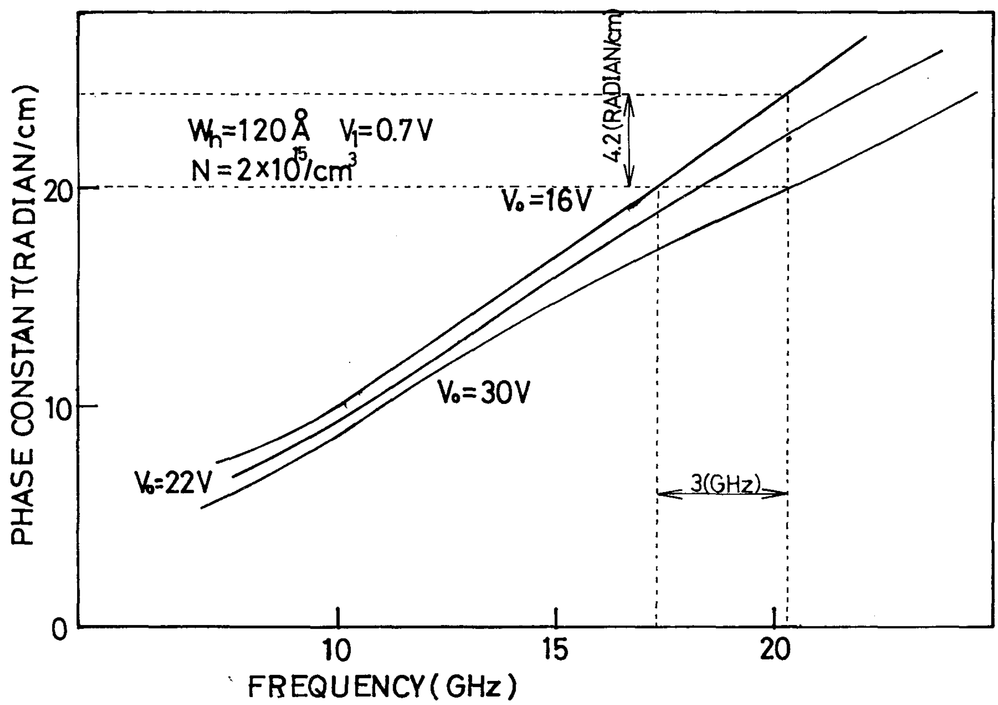

Fig.7 Phase constant versus frequency as a function of the intensity of illumination. The phase constant is affected strongly by the intensity of illumination.

Fig.6 shows the attenuation constant and the phase constant of the microstrip line as a function of frequency, which is calculated by using the results in Fig.3. In Fig.6, a negative value of the attenuation contant means that the wave grows with distance. Without illumination, the wave damps with distance. The growth rate of the wave travelling in the microstrip line increases as the optically excited electrons increase.

Fig.7 shows the phase constant versus frequency. As is clear in the figure, phase shift as high as 2π radians/cm can be achieved by illuminating the semi-transparent gate metal with above-band gap radiation. The density of electron-hole pairs are the product of the generation rate and the life time of the excited carriers. The plasma density in Fig.7 is estimated to be $3.9\times10^{14}/cm^3$. The value is three orders of magnitude less than the plasma density required for the method of vaucher et al.. The phase shifter can be used as ultra-fast and high-repetition rate modulator in the microwave frequency range.

IV Conclusions

Numerical simulation has done to investigate whether or not the space charge modes in an n-InP diode with suitably designed Schottky barrier cathode contact can be varied by illumination. It has been found that the cathode trapped domain mode changes into travelling dipole domain mode by illuminating the semi-transparent gate metal with above-band gap radiation. The susceptance of an n-InP diode with Schottky barrier cathode can be controlled by optically injecting the plasma into high field layer in the diode. Inserting this diode between a resonant microstrip lines in place of the dielectric layer, a distributed phase shifter can be realized. The phase shifts as high as 2π radians/cm have been predicted. The phase shifter has a gain as a result of the electron transfer from the lower valley with light mass to the upper valleys with heavy mass. The plasma density required for achieving the phase shifting is less than $1\times10^{15}/cm^3$. We need relatively low power laser sources for phase shifting. Ultra high-speed and high-repetition rate phase modulation is possible, since the life times of the excess carriers in n-InP are less than 100 ps.

In the present analysis, we have not considered the deep trap levels in the forbidden energy band gap. The charging and discharging time constant of the deep levels are much longer than the time scale in the present interest, thus, the deep level do not affect the operation of the phase shifter in any essential way.

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