Journal of Optics, 2005, Vol. 34, No. 4, Page 172-175

HOT ELECTRON MICROWAVE INCREMENTAL CONDUCTIVITY OF GALLIUM NITRIDE

Dutikrushna Panda, *C K Sarkar, *D Mukhopadhyay and P S Mallick

Department of Electronics and Communication Engineering
National Institute of Science and Technology
Palur Hills, Berhampur, Orissa-761 008, India
*Dept. of Electronics and Telecommunication Engineering
Jadavpur University, Kolkata - 700 032

(Received on July 28, 2005)

The microwave incremental mobility values of GaN have been calculated at 77K in presence of dc field and found that, the mobility values decreases monotonically with field. Frequency dependence of the real part of microwave conductivity is constant up to milimeter wavelength range of frequencies and the imaginary part shows a peak in submilimeter wavelength range.

1. INTRODUCTION

Galium Nitride, a direct bandgap semiconductor, has emerged as an important material for high-power, optoelectronic as well as for high temperature devices because of its large bandgap (3.4eV), strong bond strength (2.3eV/bond) and high breakdown voltage ($3 X 10^6$ V/cm) [1]. Recently the material has become more popular because of several new applications including blue light emitting diodes (LEDs), blue laser diodes (LDs) [2]. A wide energy band gap leads to a low intrinsic carrier concentration, which enables a more precise control of free carrier concentration over a wide range of temperatures and hence the device made of this kind of material will be operable at high temperatures with large break down voltage. It has been shown that GaN has a large peak electron velocity and can be an important candidate for high frequency application. Although many authors have studied the DC transport properties of GaN and other III-nitrides, the microwave conductivity studies have not received much attention. We present in this paper, the Hot electron microwave incremental conductivity characteristics of gallium nitride by solving the time dependent Boltzmann Transport equation, taking the various scattering mechanisms into consideration. The important scattering mechanisms in this material are the scattering by acoustic phonons both through deformation potential and piezoelectric coupling, ionized impurity scattering and scattering by optical phonons which are of the polar type in gallium nitride. Like in most III-V compound semiconductors, the electron mobility is predominantly determined by the polar optical phonon scattering in gallium nitride. It is also to be noted that the scatterings by ionized impurities and piezoelectric phonons are elastic and they do not contribute to the energy loss mechanism. The solution of the Boltzmann equation under predominant polar optical phonon scattering is beset with many difficulties. Polar optical phonon scattering is neither elastic nor randomizing. One cannot, therefore make the usual relaxation time approximation. The problem can be solved if one assumes that the carrier concentration in the sample is large. Under such condition energy distribution fuuction of the electrons can be assumed to be a displaced Maxwellian[3] one, with with having an electron temperature $T_E$larger than the lattice temperature T_L. The

Keywords : Optoelectronic material, nitrides, microwave

collision operators for the various scattering mechanisms can then be expanded into spherical harmonics and the series truncated after two terms, if the drift energy of the carriers is small compared with their thermal energy which is commonly known as the "diffusion approximation" [4]. These two conditions are well satisfied in gallium nitride at 77K and one can solve the momentum and energy balance equations analytically and obtain the microwave incremental conductivity characteristics. Although the technique has been widely used for many other materials, GaN did not receive much attention.

2. THEORY

The energy distribution function of the electrons becomes a displaced Maxwellian one given by

$$f(\bar{k}) = \frac{\eta^2}{\left(2\pi m^* k_B T_e\right)^{3/2}} \exp\left[\frac{-\hbar^2\left|\bar{k}-\bar{d}\right|^2}{2m^* k_B T_e}\right] \tag{1}$$

where d is the displacement in the momentum space and T_e is the electron temperature and can be obtained by solving the evergy and momentum conservation equations. The relevant balance conditions for the momentum and energy are written as,

$$\int \left|\frac{\partial f(\mathbf{k})}{\partial t}\right|_F \mathrm{k}d\mathrm{k} = \sum_i \int \frac{\partial f(k)}{\partial t}\Big|_j \mathbf{k}d\mathbf{k} \tag{2}$$

$$\int \left|\frac{\partial f(\mathbf{k})}{\partial t}\right|_F \mathrm{E}d\mathrm{k} = \sum_j \int \frac{\partial f(k)}{\partial t}\Big|_j \mathrm{E}d\mathbf{k} \tag{3}$$

where, $E = (\hbar^2 k^2)/2m^*$ is the energy of the electron and the summation is taken over all the scattering process. By assuming the diffusion approximation and considering the various scattering mechanisms we get [5].

$$\left[\frac{e}{\hbar}\right]\left[\frac{F}{d}\right] = \frac{1}{\tau_{mac}} + \frac{1}{\tau_{mpe}} + \frac{1}{\tau_{mpo}} + \frac{1}{\tau_{mimp}} \tag{4}$$

$$\left[\frac{e\hbar}{m^*}\right] Fd = \frac{3}{2} k_B T_c \left[\frac{1}{\tau_{Eac}} + \frac{1}{\tau_{Epo}}\right] \tag{5}$$

where τ_m and τ_E are respectively the momentum and energy relaxation times and the other subscripts refer to the type of the scattering mechanism. The explicit values of $\tau^{-1}_{mac,}\tau^{-1}_{mpz,}\tau^{-1}_{mimp,}\tau^{-1}_{mp0,}\tau^{-1}_{Eac,}\tau^{-1}_{Ep0}$ are given in [5,6].

Now a microwave field of the form $F_1\exp(jwt)$ is impressed upon the dc field F_0 such that $F_1 << F_0$, then the momentum and the temperature of the electron will be perturbed and the corresponding perturbation equations are given by,

$$j\omega \int f_1(k)dk = -\left[\frac{e}{\hbar}\right]F_0 + \sum_j \frac{\eta}{\partial d_0}\left|\int \frac{\partial f(k)}{\partial t}\Big|_j kdk\right| d_1 + \sum \frac{\partial}{\partial T_{eo}}\left[\int \frac{\partial f(k)}{\partial t}\Big|_j kdk\right] T_{el} \tag{6}$$

$$j\omega \int f_1(k)dE = -\left[\frac{e\eta}{m^*}\right]\left[F_0 d_0 + F_0 d_1\right] + \sum_j \frac{\eta}{\partial d_0}\left|\int \frac{\partial f(k)}{\partial t}\Big|_j Edk]\right| d_1 + \sum \frac{\partial}{\partial T_{eo}}\left[\int \frac{\partial f(k)}{\partial t}\Big|_j Edk]\right] T_{el} \tag{7}$$

where $f_1(k)$ is the asymmetric part of the distribution function and is given by
$f(k)=f_0(E)+f_1(k)\cos\theta$
θ being the angle between k and the applied dc field F_0. d_1 and T_{el} are respectively the perturbed components of the drift momentum and the electron temperature due to the applied microwave field F_1. Under the "diffusion mobility characteristics. Details of the calculation have been shown in [7] for cadmium telluride, a typical member of the compound semiconductors. When the microwave field is applied perpendicular to the dc field, the perturbation in the electron temperature can be neglected, since it is proportional to the square of the amplitude of the microwave signal and it is of second order. For the perpendicular orientation, the expression for the microwave conductivity is $\partial_{\perp} = \partial_0 /(1 + j\omega\tau_{mo})$ and the mcirowave mobility for the perpendicular orientation has been obtained from this expression.

3. RESULTS AND DISCUSSION

The microwave mobility values for gallium nitride have been calculated for different applied dc field and at different frequencies at 77K. We have shown in Figure 1, the variation of the real and imaginary parts of microwave mobility with the applied dc electric field, when the microwave field is applied parallel to the dc field and perpendicular to the dc field for a microwave frequency of 90 GHz. It is found that all the microwave mobility decrease monotonically with the applied field and it is also observed that the perpendicular mobility value at any field is higher than that of the parallel mobility. This is expected because the heating field produces a second order effect on the perpendicular mobility. The imaginary part of the microwave mobility signifies the contribution of free carriers to the complex permittivity and is negative. Fig. 1 also indicates that the microwave mobility of the real part is larger than that of the imaginary part. The imaginary parts of the both parallel and perpendicular microwave mobility are being saturated at 5kV/cm. At lower field, the real parts of the parallel and perpendicular microwave mobility coincides, similarly at the lower field the imaginary part of the parallel and perpendicular microwave mobility coincides.

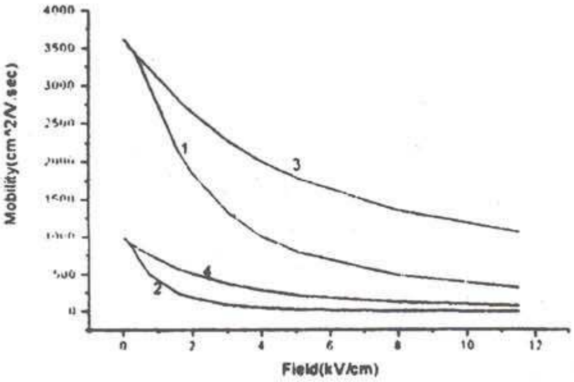

Fig. 1 : Variation of microwave electron mobility with field at 77K, impurity = 0, frequency = 90 GHz. (1) Real part of the parallel. microwave mobility, (2) Imaginary part of the parallel mocrowave mobility, (3) Real part of the perpendicular microwave mobility, (4) Imaginary part of the perpendicular microwave mobility.

Fig. 2 shows the variation of the real and imaginary parts of the parallel and perpendicular microwave mobility with frequency at 77K for an applied c field of 5kV/cm. It is found

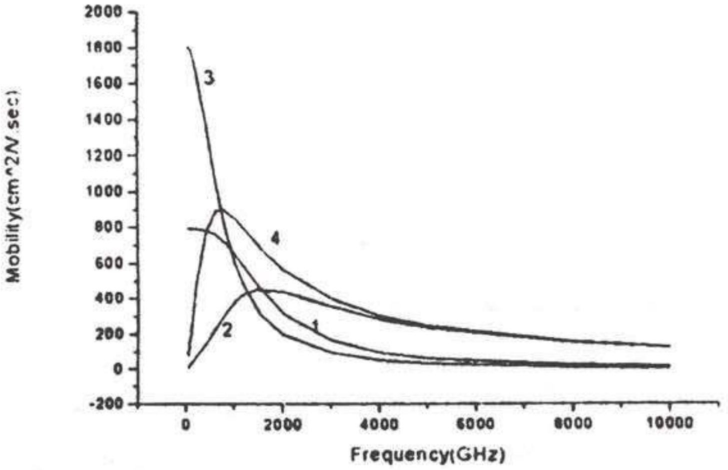

Fig. 2 : Variation of microwave electron mobility with field at 77K, impurity = 0, frequency = 90 GHz. (1) Real part of the paralle. microwave mobility, (2) Imaginary part of teh parallel mocrowave mobility, (3) Real part of the perpendicular microwave mobility, (4) Imaginary part of the perpendicular microwave mobility.

that the real part of the parallel and perpendicular microwave mobility decreases monotonically with frequency and becomes almost saturated after 5000GHz. So it can be effectively used in microwave applications in this frequency range. It is also observed that the imaginary part of the parallel and perpendicular microwave mobility show a peak around 1500GHz and 800GHz respectively. It indicates that the energy relaxation effects of the carriers in gallium nitride become prominent in the sub milimeter and infrared wavelength ranges.

4. CONCLUSION

It can be concluded that the variation of the electron mobility in gallium nitride due to application of mcrowave field can be well studied by a displaced Maxwellian calculation. The results obtained for parallel and perpendicular microwave mobility will be useful in CAD tools of microwave device designers. Thus, it can also be concluded that the gallium nitride can be effectively used in microwave devices.

5. REFERENCES

1. S.C. Jain, M. Willander, J. Van Overstracten, J. Appl. Phys., **6**, 3, (2000)
2. S. Nakamura, M. Senoh, S. Nagahama, N Iwasa, T. Yamada, T Matsusheta, H. Kiyoka and Y. Sugimoto, Jpn. J. Appl. Phys., part 2 **35**, L74(1996).
3. R. Stratton, "Proc. R. Soc. London", Ser A, **246** : 406, (1958)
4. L. Stenflo, "Proc. IEEE", **54** : 1966, (1970)
5. B. R. Nag, "Electron transport in compound semiconductors", Berlin : Springer Verlag, 283, (1980).
6. D. Mukhopadhyay, D. P. Bhattacharya, "J. Phys. Chem. Solids", **45** : 393, (1984).
7. D. Chakraborty, M. K. Mukherjee, D. Mukhopadhyay, "Microwave and Optical Tech. Lett.", **4** : 244, (1991).