# Infrared absorption at the LO phonon energy of metal/ semiconductor/metal composite materials

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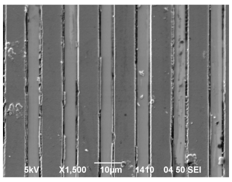
***Abstract*—Interaction of a semiconductor surface or interface and p-polarized infrared light has been investigated from the viewpoint of THz application. In this study the electric dipole absorption at the resonant energy to a longitudinal optical phonon is clearly observed also for s-polarization for lateral Ti/GaN/Ti and Ti/GaAs/Ti stripe structures. Modification of permittivity is found by the analysis of Raman and IR spectra.**

## I. INTRODUCTION

The interaction between infrared light and phonon-plasmon systems has been discussed in many articles. Since Berreman has found a sharp drop in the p-polarized infrared (IR) reflectance (IRR) spectrum of a LiF film backed by silver around the longitudinal optical (LO) phonon energy [1], IR absorption, reflectance loss by interface polariton generation, and so forth were discussed as the possible sources. The restoring force produced by the polarization charges at the surface or interface was discussed for the plasmon mode in thin films [2]. After several discussions regarding the effects of interference and the virtual mode [3,4], along with an investigation of the experimental reflectance spectra of samples of undoped (u)-GaAs/ n-type (n)-GaAs substrates, Schubert *et al.* concluded that the surface or interface phonon-plasmon polariton modes are the origin of the reflectance loss [5]. One of the present authors clarified the respective contribution of these factors using attenuated total reflectance method of a GaN thin film by the incidence of p-polarized IR light on an (0001) surface in the Otto configuration [6]. It was found that the observed small reflectance loss at the LO phonon energy (730-740 cm$^{-1}$) exhibited no energy shift by the variation of the magnitude of the wavevector parallel to the interfaces ($k_{//}$). This reflectance loss was attributed to the absorption because of the electric dipolemoment caused by the polarization charges at the surface and interface with the substrate. Although the weakness of the absorption was attributed to the small amplitude of the electric field of the light that penetrated the interface, the observation of a more intense absorption is desired to identify the model of the generation of dipolemoment.

Thus far, metal/dielectric composite structured materials have been investigated to control the permittivity and permeability[7]. Resonators for plasmon-electromagnetic wave coupling and amplification of electromagnetic waves were investigated. These studies analyzed the coupling of the electronic plasmon but not that of the phonon [8-13].

Many articles have discussed emission of electromagnetic waves related to the LO phonon [14 - 21]. It was found that the ultrafast excitation of carriers and the resultant fast initial rise of the polarization cause the THz radiation. Although these radiations were induced by short pulse excitation, the long coherence of several ps demands further mechanism. Thus the generation mechanism of the LO-resonant electric dipolemoment surviving over several ps or continuously is of great interest. In this article, we report a strong IR absorption at the LO phonon energy in a metal/semiconductor composite materials based on theoretical function of permittivity.



## II. EXPERIMENTAL

The mesa-stripe structures of GaN and GaAs were fabricated. Undoped GaN thin layers on sapphire (0001) substrates and undoped GaAs (001) substrates were etched as mesa stripe structures with approximately 6 μm width of etched regions and a period of 14 μm. Two types of samples were fabricated: with Ti metal deposition in the etched regions and without the Ti deposition. A SEM image for Ti/GaAs structures is shown in Fig. 1. The residual electron density in the region of approximately 1μm from the surface of the GaN samples was on the order of $10^{16}$ cm$^{-3}$. The electron density of GaAs was less than $1\times10^{16}$ cm$^{-3}$. IRR measurements were performed by the incidence angle of 30° from the surface normal. Raman spectra were obtained by the back scattering geometry using a 532-nm laser beam.

## III. RESULTS

Figure 2 shows the dependence of the IR reflectance spectrum on polarization direction for two GaN samples with and without the Ti/GaN stripes. When the incidence direction is parallel to the stripes, the electric field ***E*** of the s-polarized light is perpendicular to the stripes (***E***⊥stripe line). For the incidence of perpendicular to the stripes, ***E*** of the s-polarized light is parallel to the stripe line (***E***//stripe line). The two spectra in Fig. 2(a) of the sample without the Ti stripes agree except for the two dips at 687 and 716cm$^{-1}$. These dips are

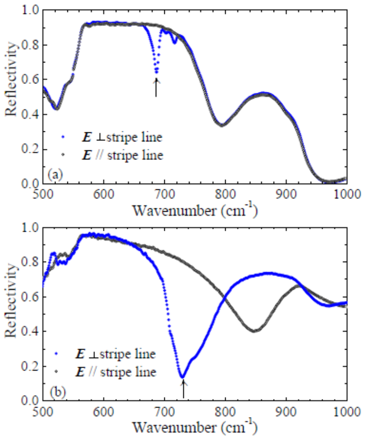
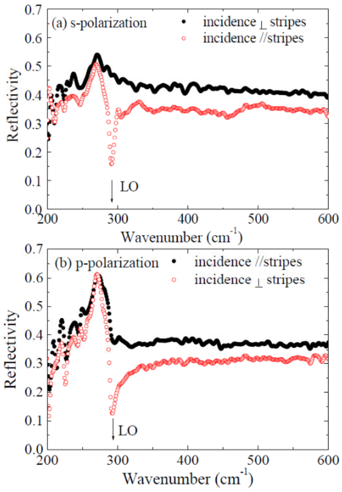


Fig.2 IR reflectance spectra of s-polarized light for the u-GaN film.



thought to originate from waveguide effect, since the lateral waveguide structures of five cycles of the Ti/GaN strip agree with the wavelength of the dip positions. Figure 2 (b) exhibits the dramatic difference in the spectrum shape between the two electric field directions. The eminent reflectance loss of the light with ***E*** perpendicular to the stripe lines appears at the LO phonon energy.

Figure 3 shows the result for the GaAs case. The spectra are for the four incidence patterns characterized by the polarization direction and the incidence direction. When the incidence direction is parallel to the stripes, ***E*** of the s-polarized light is perpendicular to the stripes, while ***E*** of the p-polarized light has such a component when the incidence is perpendicular to the stripes. The sharp reflectance loss at the LO phonon energy in Fig.3, reflecting the low electron density and high crystal quality, exhibits that the reflectance loss takes place for ***E*** perpendicular to the metal/semiconductor interfaces.

Figure 4 shows the Raman spectra for GaN/Ti structures. Only when the incident spot covers both of the two interfaces of Ti/GaN, an additional peak is found beside the LO peak at approximately 750 cm$^{-1}$[22]. The function of permittivity is expressed as the sum of the term affected by the interface charges $\varepsilon_l(\omega)$, the term of the TO phonon $\varepsilon_T(\omega)$, and $\varepsilon(\infty)-\varepsilon_0$.

$$\varepsilon(\omega)=\varepsilon(\infty)+\varepsilon_T(\omega)+\varepsilon_l(\omega)-\varepsilon_0. \tag{1}$$

$$\varepsilon_l(\omega)=\varepsilon_l(\infty)+B_+\eta_++B_-\eta_- \tag{2}$$

$$B_\pm=\frac{\pm1}{C_\pm}\left\{\varepsilon_0\omega_L^2\left(\frac{1}{\varepsilon_r(\infty)}-\frac{1}{\varepsilon_r(0)}\right)\left(\frac{\omega_L^2-\omega_\mp^2}{\omega_+^2-\omega_-^2}+\frac{\omega_p^2}{\omega_+^2-\omega_-^2}\right)\right. \tag{3}$$

$$\left.+\frac{\varepsilon_0}{\varepsilon_r(\infty)}\left[\frac{\left(\omega_+^2-\omega_L^2\right)\left(\omega_L^2-\omega_-^2\right)}{\omega_+^2-\omega_-^2}+\frac{\omega_p^2\left(\omega_\pm^2-\omega_L^2\right)}{\omega_+^2-\omega_-^2}\right]\right\},$$

Here, $\eta_\pm=C_\pm/(\omega_\pm^2-\omega^2-\gamma_\pm\omega)$, $\varepsilon_l(\infty)=(2\varepsilon(\infty)-\varepsilon_0)/\varepsilon_r(\infty)$, and $\varepsilon_r(\infty)=\varepsilon(\infty)/\varepsilon_0$.[22] The physical constants were obtained from references.[23, 24] An additional peak in the imaginary part at the LO phonon energy and a new zero point of the real part in 750-760 cm$^{-1}$ are found in Fig. 5. The large energy difference between the TO and LO phonon energies of GaN produced this zero point. The coincidence of these energies with the observed respective energies of reflectance loss and the new Raman peak suggests that the stripe/semiconductor structure induces the dielectric absorption at the LO phonon energy.

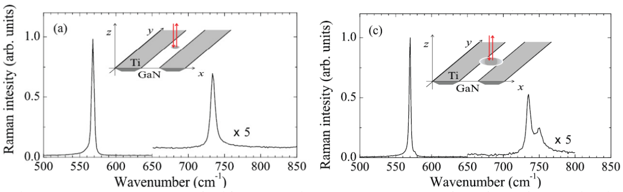


Fig.4 Raman spectra of Ti/GaN-stripe structures. Only when the excitation laser is incident on both of the two GaN/Ti interfaces an additional peak indicated by an arrow was found[22].

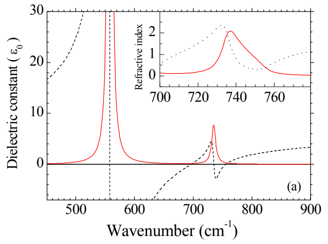


Fig.5 Theoretical permittivity of the Ti/GaN composite.

## IV. CONCLUSION

The permittivity of semiconductor/metal composites using IR absorption and Raman measurements was investigated. The generation of the lateral dipolemoment in the LO phonon energy region is found. This dipolemoment would be significant for the surface emission in THz region.

## REFERENCES

[1] D. W. Berreman, Phys. Rev. **130**, 2193 (1963)

[2] C. Kittel, Introduction to Solid States Physics, Wiley, New York, 1986

[3] R. Fuchs, K. L. Kliewe, and W. J. Pardee, Phys. Rev. **150**, 589 (1966)

[4] K. L. Kliewer and R. Fuchs, Phys. Rev. **150**, 573 (1966)

[5] M. Schubert, T. Hofmann, and Jan Šik, Phys. Rev. B **71**, 035324 (2005)M. Schubert, T. Hofmann, and Jan Šik, Phys. Rev. B **71**, 035324 (2005)

[6] Y.Ishitani, J. Appl. Phys. **112**, 063531 (2012)

[7] T. A. Klar, A. V. Kildishev, V. P. Drachev, and V. M. Shalaev, J. Select. Top. Quant. Elect. **12**, 1106 (2006)

[8] S. A. Mikhailov, Phys. Rev. B 58, 1517 (1998)

[9] Y. Lyaschuk and V. V. Korotyeyev, Ukr. J. Phys. Opt. **13**, 142 (2012)

[10] J. Han, J. Gu, X. Lu, M. He, Q. Xing, and W. Zhang, Opt. Exp. **17**, 16527 (2009)

[11] G. Dayal and S. A. Ramakrishna, Opt. Exp. **20**, 17503 (2012)

[12] G.-Q. Liu, Y. Hu, Z.-Q Liu, Y.-H. Chen, Z.-J. Cai, X.-N. Zhang, and K. Huang, Phys. Chem. Phys. **16**, 4320 (2014)

[13] G. Dayal and S. A. Ramakrishna, Opt. Exp. **22**, 15104 (2014)

[14] X. –C. Zhang, B. B. Hu, J. T. Darrow, and D. H. Auston, Appl. Phys. Lett. 56, 1101 (1990)

[15] A. V. Kuznetsov and C. J. Stanton, Phys. Rev. B 48, 10828 (1993)

[16] A. V. Kuznetsov and C. J. Stanton, Phys. Rev. B 51, 7555 (1995)

[17] T. Dekorsy, H. Auer, H. J, Bakker, H. G. Roskos, H. Kurz, V. Wanger, and P. Grosse, Phys. Rev. Lett. 74, 738 (1995)

[18] M. Tani, R. Fukasawa, H Abe, K. Sakai, and S. Nakashima, J. Appl. Phys. 83, 2473 (1998)

[19] K. Mizoguchi, T, Furuichi, M. Nakayama, S. Saito, A. Syouji, and K. Sakai, Appl. Phys. Lett. **87**, 093102 (2005)

[20] K. Mizoguchi, Y. Kazawa, S. Saito, K. Sakai, N. Nakayama, Appl. Phys. Lett. **94**, 171105 (2009)

[21] S. Tsuruta, H. Takeuchi, H. Yamada, M. Hase, and M. Nakayama, J. Appl. Phys. **113**, 143502 (2013)

[22] Y. Ishitani, K. Hatta, K. Morita, and B. Ma, J. Phys. D **48**, 095103 (2015)

[23] M. Schubert, T. E. Tiwald, C. M. Herzinger, Phys. Rev. B **61**, 8187 (2000)

[24] A. Kasic, M. Schubert, B. Kuhn, F. Scholz, S. Einfeldt, and D. Hommel, J. Appl. Phys. **89**, 3720 (2001)