MODIFICATION OF THE INTRINSIC PROPERTIES OF GALLIUM ARSENIDE, GALLIUM PHOPHIDE AND SILICON CARBIDE SAMPLES UNDER LIGHT AT CRYOGENIC TEMPERATURES

David Mouneyrac[1,2], John G. Hartnett[2], Jean-Michel Le Floch[2], Jerzy Krupka[3], Michael E. Tobar[2] and Dominique Cros[1]

[1]XLIM UMR 6172, Université de Limoges / CNRS, 123 Avenue Albert Thomas, 87060 Limoges Cedex, France

[2]School of Physics, University of Western Australia, 35 Stirling Hwy, Crawley, 6009, Western Australia, Australia

[3]Institute of Microelectronics and Optoelectronics, Warsaw University of Technology, Warsaw 00-662, Poland

david.mouneyrac@xlim.fr

ABSTRACT

Gallium Arsenide, Gallium Phosphide and Silicon Carbide, which are all semiconductors, have been examined at cryogenic temperature with and without illumination at various wavelengths. Illumination causes a modification of the intrinsic properties of the materials such as a change in permittivity and an increase in conductivity. This phenomenon can be explained by a change of state of the free carriers in different bands of the semiconductors.

INTRODUCTION

The whispering gallery mode (WGM) method has been used to make the most accurate measurements of the complex permittivity of extremely low-loss dielectric materials. This method has been employed for very precise measurements of the permittivity and the dielectric losses of both isotropic and uniaxial anisotropic materials [1-4] and also to analyze the effect of the light on Gallium Arsenide (GaAs) and Gallium Phosphide (GaP) samples under a white light at cryogenic temperatures [5],[6]. Recently, further experiments on high purity GaAs, GaP and 4H Silicon Carbide (4H-SiC) samples have been measured at different wavelengths in order to provide an explanation of the observed phenomenon.

DESCRIPTION

GaAs, GaP and 4H-SiC are high purity semi-conductors with an energy band gap equal to 1.51, 2.33 and 3.25eV respectively at 50K. An electric field such as a light under certain conditions can cause the free carriers to move in the semi-conductor, generating a current and then modifying the properties of the material. GaAs, GaP and 4H-SiC materials have been studied under light at cryogenic temperature. We observed a change in the frequency (f) of the resonant mode being measured,. The latter may be interpreted as a modification of the material permittivity according to,

$$\frac{\Delta f}{f} = -\frac{1}{2} p_e \frac{\Delta \varepsilon_r}{\varepsilon_r}, \qquad (1)$$

where $\Delta f = f - f_0$ and f_0 is the initial frequency of the measured mode.

p_e is the electric filling factor of the resonant mode

ε_r is the initial permittivity of the material

An increase of the losses was also observed, and may be described by,

$$\tan\delta = \tan\delta_d + \frac{\sigma_0}{\omega\varepsilon_0\varepsilon_r} + \frac{\Delta\sigma}{\omega\varepsilon_0\varepsilon_r} \quad \textbf{(2)}$$

The two first terms of this equation are related to properties of the material in darkness and the last term is related to a modification of the conductivity after the sample is exposed to light and after the illumination is switched off. This term describes the effect of the change of state of the free carriers under exposure to light.

EXPERIMENTAL SETUP

The measurements were taken on cylindrical high-purity samples of GaAs (diameter = 25.39mm and height = 6.25mm), GaP (diameter = 48.12mm and height = 5mm) and 4H-SiC (diameter = 11mm and height = 2.63mm). The different samples were placed in a closed cavity connected to a vector network analyser (VNA) (Figure 1). Different light sources were used to illuminate the semiconductor (SC) samples via an optical fibre. A 10mW white light and three different 1.4mW lasers (red (633nm), green (532nm) and blue (402nm)) were used to illuminate the samples. The cavity was located in a vacuum chamber and cooled on the cold finger of a single stage cryocooler. Once the temperature of the sample stabilized, the chosen resonant mode frequency and Q-factor were recorded via a fast data acquisition system. The sample was then illuminated for a certain time until the mode frequency stabilized after which the light was switched off.

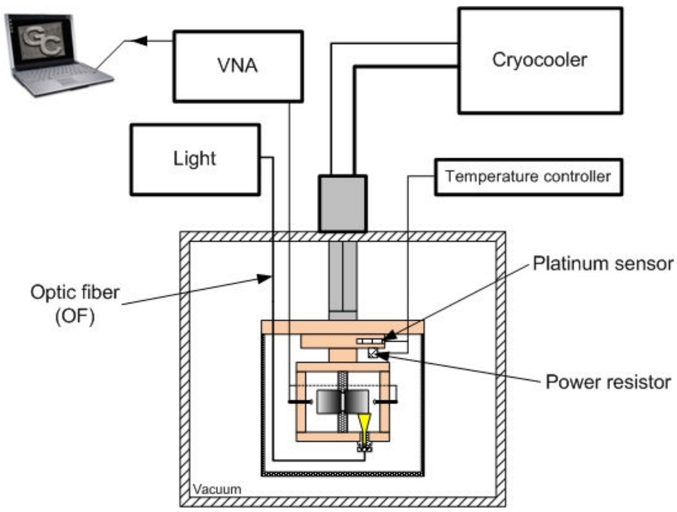

Figure 1 : (color online) The experimental setup

RESULTS

Measurements on GaP

The $WGE_{11,0,0}$ and $WGE_{20,0,0}$ modes, respectively, at 10.9GHz and 16.5GHz, at 50K, were used for this first experiment. A 10mW power white light was sent to the sample and both frequencies recorded. The figure 2 and 3 show the evolution of the relative permittivity and microwave losses in the GaP sample under illumination . Due to different electric field distributions in the two modes, the light illuminated “more field” in the case of the $WGE_{20,0,0}$. As a result, it is clear that the effect of the light is stronger in the second mode. This can be explained by the fact that the light modifies the properties of the semi-conductor material where the field is confined.

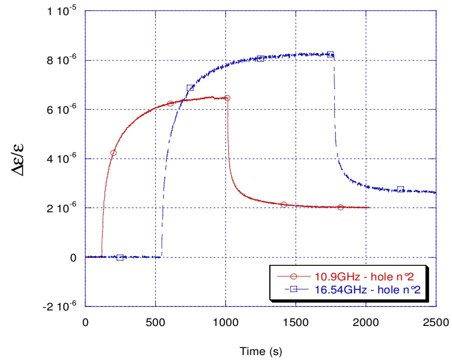

Figure 2 : (color online) The evolution of the relative permittivity as a function of time for two different measured modes in the GaP sample at 50K

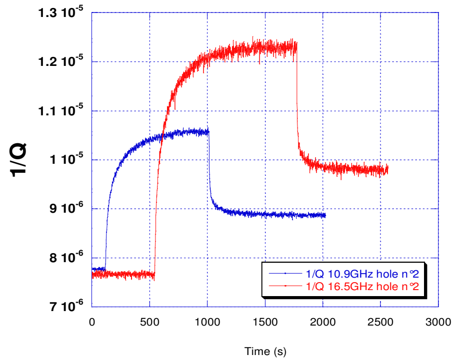

Figure 3 : (color online) The evolution of the reciprocal of the quality factor (or microwave losses) as a function of time for two different measured modes in the GaP sample at 50K

In the second experiment, GaP was measured where three 1.4mW different coloured lasers (red, green and blue) were used to illuminate the sample. The $WGE_{11,0,0}$ mode was used and the resulting measured microwave losses are plotted in figure 4. We observed a bigger increase in the losses when the sample was under red light and almost no effect under blue light. Considering the energy of the incident photon ($E_{ph}=h\nu$), the energy of the red, green and blue photons have energies equal to 1.9, 2.3 and 3.2eV. The energy gap of GaP semi-conductor is known to be 2.33eV at 50K, but the band to band transition is not responsible to the observed modification of the microwave properties of the sample as the energy of the red photon is not high enough to facilitate the transition.

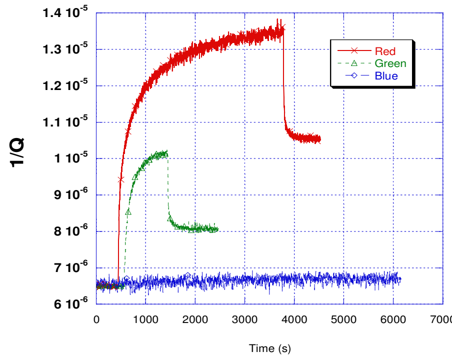

Figure 4 : (color online) The evolution of the reciprocal quality factor (or microwave losses) of the GaP sample under red, green and blue lights at 50K

Measurements on GaAs

The GaAs sample was measured with the three lasers using the $WGH_{7,0,0}$ mode at 12.54GHz to characterise the effect of illumination. In this case, the energy of the incident red, green and blue photons is larger than the energy gap of the GaAs semi-conductor (1.51eV at 50K). Under green light, the measured mode disappears almost instantaneously into the noise floor of the VNA. The time it takes was too fast to be measured using our standard data acquisition software. Under red and blue light, the effect is similar to that observed in GaP.

Measurements on 4H-SiC

In the 4H-SiC sample, the TE_{011} mode was measured under red, green and blue light. Its frequency was near 10.9GHz at 50K. Figure 5 shows the evolution of its relative permittivity as a function of time, at 50K. This was calculated to be nearly the same regardless of the colour (wavelength) of light used. The lasers were powered using an external power supply and it was not easy to set the exact same power when we changing over to a different laser. This may explain the small differences. Also, in the case of the 4H-SiC sample under illumination by any of the red, green and blue lasers, the energy of the incident photons is lower than the energy gap of 4H-SiC (3.25eV at 50K). Again, the band to band transition cannot be the explanation for the observed effect because it is not allowed.

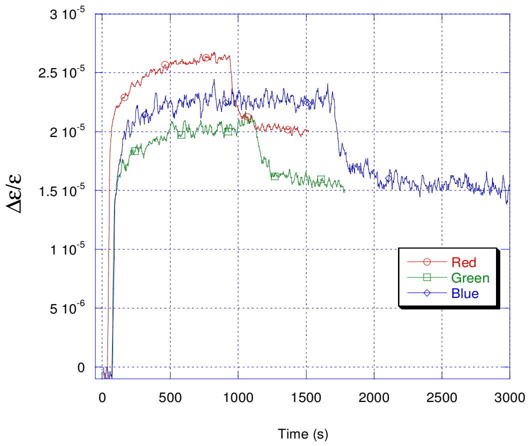

Figure 5 : (color online) The evolution of the relative permittivity of the 4H-SiC sample under red, green and blue light at 50K

CONCLUSION

The paper shows a modification of the microwave properties of the GaP, GaAs and 4H-SiC semi-conductor materials under light at cryogenic temperatures. The first conclusion is that the properties of the sample are modified only if the light is illuminated a zone where the electromagnetic field is confined. And in both GaP and 4H-SiC, we have shown an effect is observed under illumination even if the energy of the incident photons is lower than the energy gap of the semi-conductor. This may be explained by the fact that the samples have been unintentionally doped during the manufacturing process. Impurities with energy levels in the band gap might be related to the observed effect.

ACKNOWLEDGEMENTS

This work was supported by the Australian Research Council. We would like to thank the Institute of Electronic Materials Technology, 133 Wolczynska St., 01-919 Warsaw, Poland for supplying the semiconductor samples.

REFERENCES

[1] J. Baker-Jarvis, R. G. Geyer, J. H. Grosvenor, Jr., M. D. Janezic, C. A.Jones, B. Riddle, C. M. Weil, and J. Krupka, IEEE Trans. Dielectr. Electr. Insul. 5, 571 (1998)

[2] J. Krupka, K. Derzakowski, A. Abramowicz, M. E. Tobar, and R. G. Geyer, Proceedings of IEEE MTT Int. Micr. Sym. Digest, Denver, 1997 (unpublished), pp. 1347-1350.

[3] J. Krupka, K. Derzakowski, M. E. Tobar, J. G. Hartnett, and R. G. Geyer, Meas. Sci. Technol. 10, 387 (1999).

[4] J. Krupka, D. Mouneyrac, J. G. Hartnett, and M. E. Tobar, IEEE Trans. Microwave Theory Tech. 56, 1201 (2008).

[5] J. G. Hartnett, D. Mouneyrac, J-M. Le Floch, J. Krupka, M. E. Tobar and D. Cros, Appl. Phys. Lett. 93, 062105 (2008)

[6] J. G. Hartnett, D. Mouneyrac, J-M. Le Floch, J. Krupka, M. E. Tobar and D. Cros, J. Appl. Phys. 104, 113714 (2008)