Observation of persistent photoconductivity and modified permittivity in bulk Gallium Arsenide and Gallium Phosphide samples at cryogenic temperatures

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***Abstract*—The whispering gallery modes have been used to characterize the effect of the light on gallium arsenide and gallium phosphide placed in darkness at 50K at frequencies respectively equal to 18.94GHz and 11.54GHz. The experiment shows a change in the polarization state of the semiconductor, which is consistent with a free electron-hole creation/recombination process. The permittivity and the loss tangent of the semiconductor are modified by shifting of the free electrons from the valence band to the conduction band.**

I. 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, both ceramic and crystalline. The method has been employed for very precise measurements of the permittivity and the dielectric losses of both isotropic and uniaxial anisotropic materials.[1-3] The WGM technique has also been used to characterize the complex permittivity of semiconductors, including bulk gallium arsenide (GaAs) and gallium phosphide (GaP) [4], at microwave frequencies from cryogenic temperatures to room temperature.

In the paper, we present the measurement of a change of the permittivity [5] and the quality factor [6] resulting from polarization changes in the semiconductors GaAs and GaP under white light at cryogenic temperature.

II. DESCRIPTION

GaP and GaAs are two semiconductor materials with a isometric-hexoctahedral crystal system. One difference between GaP and GaAs is the band gap energy which is respectively equal 2.33eV [7] and 1.51eV [8] at 50K. If the energy of an incident photon $\hbar\omega$ is higher than the energy gap of the semiconductor Eg, the law of conservation of energy allows the direct transition band to band between the valence band Ev and conduction band Ec. Then, there is a generation of an electron-hole pair. A trap-assisted generation can also occur when an electron falls into a "trap", an energy level within the bandgap caused by the presence of a foreign atom or a structural defect. Once the trap is filled it cannot accept another electron [7]. If the energy of the incident photon $\hbar\omega$ is lower than the energy gap, the transition band to band is not allowed. The light can be absorbed by a different process called secondary band gap process. In that case, absorption by the free carriers, formation of excitons or photon absorption may occur. Once the light source is switched off, a recombination process from the conduction band to the valence band is allowed [9]. In the case of the whispering gallery mode, where the field is confined close to the air-dielectric interface, the position of the light has an impact on the state change of the electrons (cf. IV).

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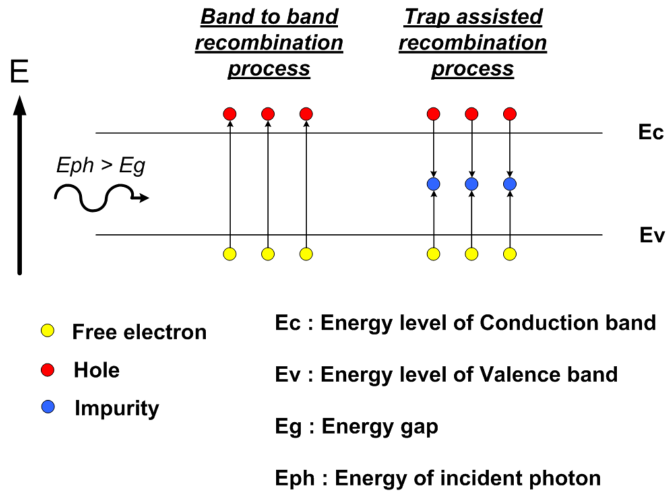

Fig.1: Energy diagram for band to band recombination process and trap assisted recombination process

III. EXPERIMENTAL SETUP

The measurements were done on cylindrical pure samples of GaAs (diameter = 25.39mm and height = 6.25mm) and GaP (diameter = 48.12mm and height = 5mm). The resonators were coupled with magnetic probes connected to a vector network analyzer. The resonators were cooled to 50K with a cryocooler. At that temperature, we selected a whispering gallery mode with a high azimuthal number (m). For the GaAs sample, the frequency of the chosen mode was 18.949GHz with m = 13 and an electric energy filling factor $p_e = 0.98577$. For the GaP sample, the frequency of the chosen mode was 11.544GHz with m = 12 and an electric energy filling factor of 0.96672.

The frequency, the unloaded quality factor and the coupling coefficient were measured using the vector network analyzer. A fast data acquisition system was implemented.

Each sample was measured under white light sent into the cavity via an optical fiber (Fig.2).

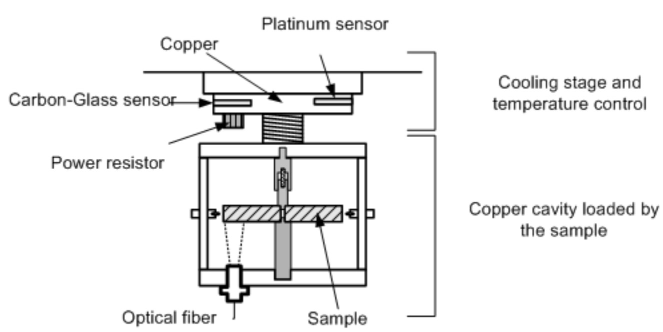

Fig.2 : Experimental setup

From the measured frequency data we calculated its derivative to deduce the derivative of the real part of the permittivity:

$$\frac{\Delta f}{f} = -p_e \frac{\Delta \varepsilon_r}{\varepsilon_r}$$

Where $\Delta f = f - f_0$, f_0 is the initial frequency of the mode

pe: electric filling factor of the measured mode

ε_r : initial permittivity of the material

IV. RESULTS

A. Short term effect of the light

Both samples were characterized with the white light switched for 30 minutes then after it was switched off, for two different positions of light. One position (hole n°1) radiated a zone on the semiconductor where the electromagnetic field has a much smaller energy density than the zone where the second hole (hole n°2) illuminated (Fig.3).

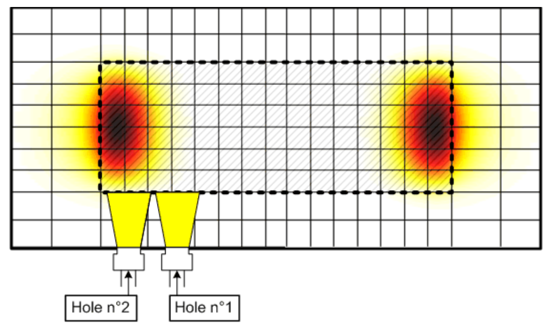

Fig.3: Position of the light

The evolution of the frequency was tracked with our fast data acquisition system. Figures 4 and 5 show the evolution of the parameter $\Delta\varepsilon_r/\varepsilon_r$ for both GaAs and GaP samples.

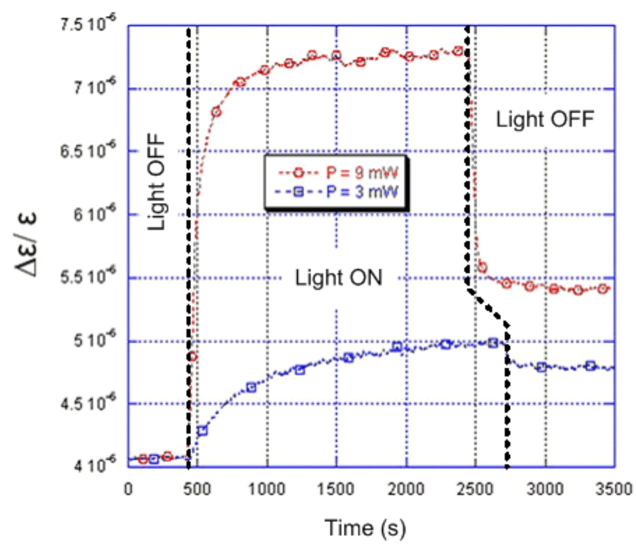

Fig.4: Variation of $\Delta\varepsilon_r/\varepsilon_r$ at 50K for GaP under light then in darkness with different light intensity powers

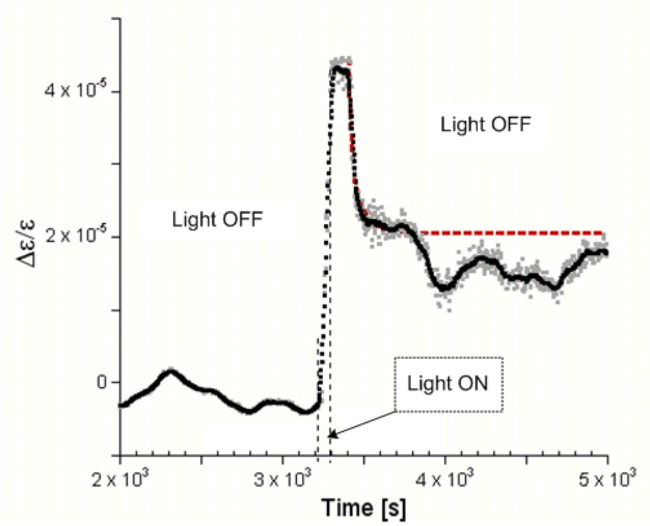

Fig.5: Variation of $\Delta\varepsilon_r/\varepsilon_r$ at 50K for GaAs under light with a light intensity power of 1mW then in darkness

The figure 4 clearly shows two time constants, one when the light is switched ON and one when the light is switched OFF. Since the GaAs sample is much more sensitive to the light than the GaP sample, it was difficult to observe the same phenomena (Fig.5). However, both figures show the presence of persistent current [10-12] which do not allow the free electrons in the conduction band to come back to their initial state in the valence band. Therefore, the light generates a change of the intrinsic properties of the materials, and so, a modification of their permittivity. It is also possible to notice the effect of the light power on both time constants and the permittivity of the GaAs and GaP samples. This change is due to a state change of the electrons moving from one band to another one (cf.II).

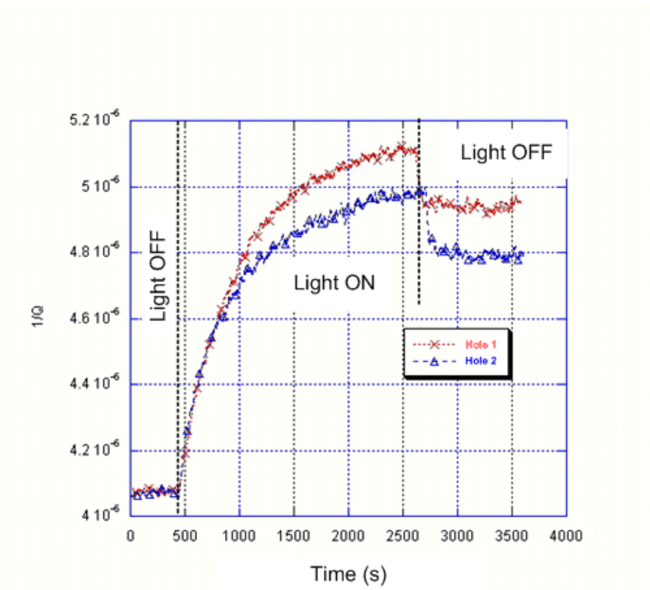

Fig.6: Variation of 1/Q at 50K the GaP sample for different positions of the light source with a light power of 3mW

The position of the light has also an effect on the change of the intrinsic properties of the samples. In this case the losses represented by the reciprocal of the Q-factor are shown in Fig. 6. When the light is sent to the zone where the electromagnetic field is low intensity (hole n°1), the shift in the frequency is less than when the light is sent to the zone where the field is high intensity (hole n°2) (Fig.6). It means that the incident photons from the white light only act on the illuminated zone and not on the entire sample.

Different time constants were measured in GaP sample and are listed in the table I.

Table I: Time constants measured for the GaP sample at 50K for different powers and different positions of the light

GaP	Light transition	Time constant (s)	
		Hole 1	*Hole 2*
P = 9 mW	ON – OFF	38	52
	OFF – ON	22	38
P = 3 mW	ON – OFF	469	439
	OFF – ON	34	28

B. Long term effect of the light

To verify the presence of persistent current [10-12] after switching off the light, we recorded for a long time the evolution of the permittivity and loss tangent of the GaP. Figure 7 shows the persistence in the reciprocal Q-factor. Indeed, once the light is switched off, the value of the reciprocal Q-factor stabilizes and never comes back to its initial value. In order to "reset" the sample, i.e. to get the electrons back to their initial values, it is necessary to warm the sample up to near room temperature.

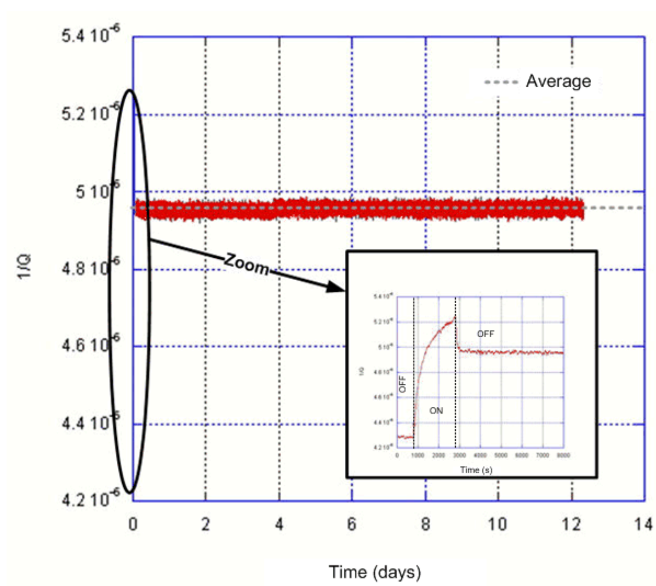

Fig.7: Evolution of 1/Q of the GaP sample recorded during several days at 50K. Initially, the light was switched ON then switched OFF.

V. CONCLUSION

To our knowledge, these are the first measurements of modified permittivity and losses at microwave frequencies in bulk semiconductors resulting from a state change of electrons from one band to another one. Others experiments are in progress in order to determinate possible applications as tunable filters versus the bulk semiconductor and the light source used.

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