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Influence of Bi on dielectric properties of $GaAs_{1-x}Bi_x$ alloys

K. ULUTAS[1], S. YAKUT[1], D. BOZOGLU[1], D. DEGER[1,*], M. ARSLAN[2], A. EROL[1]

[1]Istanbul University, Science Faculty, Physics Department, Vezneciler, 34459, Istanbul, Turkey
[2]Sakarya University, Faculty of Arts and Sciences, 54187, Sakarya, Turkey

Pure GaAs and $GaAs_{1-x}Bi_x$ alloys with different Bi ratios (1 %, 2.5 %, 3.5 %) fitted with silver contacts were measured with a dielectric spectroscopy device. Dielectric characterization was performed at room temperature in the frequency range of 0.1 Hz to 1 MHz. GaAs exhibits three relaxation regions corresponding to space-charge, dipolar and ionic polarizations in sequence with increasing frequency while $GaAs_{1-x}Bi_x$ samples show only a broad dipolar polarization in the same frequency range. This result proves the filling of the lattice with Bi through making a new bonding reducing the influence of ionic polarization. This finding supports the previous results concerning optical properties of $GaAs_{1-x}Bi_x$, presented in the literature.

Keywords: *$GaAs_{1-x}Bi_x$, alloys; dielectric properties; dielectric modulus*

1. Introduction

III-V semiconductor alloys containing Bi have recently attracted much attention due to their properties related to large bandgap reduction with increasing Bi content and large spin-orbit bowing [1]. Among them, $GaAs_{1-x}Bi_x$ alloys have unusual and unique physical properties and thus these alloys provide potential applications for fundamental physics and for a wide variety of devices in telecommunication, solar cells, spintronics, photovoltaics and laser diodes operating in 1.3 µm to 1.6 µm spectral range with improved operational efficiency and temperature sensitivity [2–4]. The GaAsBi alloy made of a semimetallic GaBi and a semiconducting GaAs has been successfully grown [5]. The doping of a small percentage of bismuth into gallium arsenide changes the valence band structure and reduces the band gap of the compound [6]. In the literature [7, 8], several works have been focused on the study of the impact of laser irradiation on GaAsBi/GaAs quantum wells, band structure, photovoltaic characterization, structural and electronic properties of GaAsBi. The effect of Bi in Bi-doped GaAs barrier layers on the structural and optical properties of InAs/GaAs quantum-dot heterostructures has been studied [9], while the study on the correlation between overpotential and nucleation process, nucleation process and structural, electrical properties has been reported in another works [10, 11]. Besides, the nonlinear optical properties of GaAsBi semiconductor have been reported in the literature [12]. Despite the importance of these alloys for optoelectronic and electronic applications, dielectric properties of GaAsBi have rarely been studied.

This work aims to define the effect of the presence of Bi in GaAs buffer via frequency dependence of dielectric relaxation. The dielectric characteristics are interpreted to shed a light on the phenomena and make up the lacks in the literature.

2. Experimental

Molecular beam epitaxy (MBE) was used to produce the $GaAs_{1-x}Bi_x$ alloys. The alloys were grown on (1 0 0) semi-insulating GaAs substrates. The growth rate for all samples was 1 mm/h. The Bi content in the samples was determined by atomic force microscopy (AFM) and Raman spectroscopy methods [3]. Electrical contacts with a 5 mm diameter were deposited on both sides of the samples prepared in 10 mm × 10 mm dimensions. Copper wires fixed by indium on silver-paste electrodes were used as electrical contacts. All samples were

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[*] E-mail: deger@istanbul.edu.tr

annealed at the maximum temperature of 373 K under vacuum pressure of 1.33×10^{-2} Pa for one hour before the measurement. Depending on the stabilization process, the capacitance C and dissipation factor tanδ of the samples were measured with reproducible results using a Novocontrol Alpha, a high-performance frequency analyzer, operating in a wide frequency range from 0.1 Hz to 1 MHz at room temperature. During the measurements, it was observed that the contact is ohmic. The samples had parallel plate capacitor configuration. The dielectric constant κ' is given by:

$$\kappa' = \frac{Cd}{\varepsilon_0 A} \tag{1}$$

where d, A, ε_0 and C are the thickness of the dielectric material, the surface area of the capacitor, the dielectric permittivity of vacuum, and the capacitance of the sample, respectively. The relation between the real ε_1 and the imaginary part (loss factor ε_2) of dielectric constant is called dissipation factor or loss tangent (tan δ) and it is given by the term $\tan\delta = \frac{\varepsilon_1}{\varepsilon_2}$.

3. Results

The frequency dependent capacitance and dielectric dissipation factor were measured, and the dielectric constant was derived from the equation 1 [13].

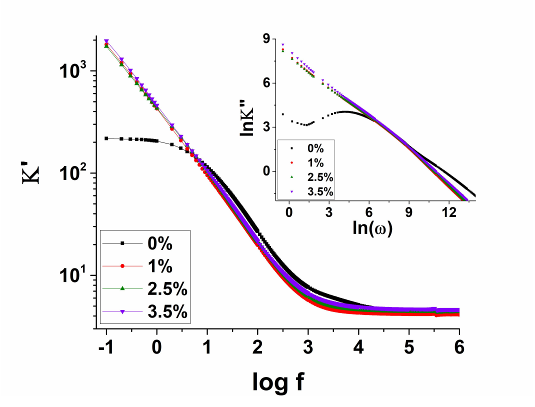

Fig. 1. Frequency dependence of dielectric constant at various component ratios. The inset shows the frequency dependence of dielectric loss.

Frequency dependence of dielectric constant for GaAs and $GaAs_{1-x}Bi_x$ is shown in Fig. 1. The dielectric constant of GaAs decreases with increasing frequency. The dielectric constant of GaAs buffer is 4.4 at 100 kHz and higher frequencies.

The dielectric constant of GaAs exhibits two different polarization mechanisms. One of them is observed at frequencies lower than 10 Hz and it can be attributed to electrode polarization. The slope obtained from dielectric loss versus frequency graph in the inset of Fig. 1 is –0.26 and this value is lower than –1, so it suggests the presence of electrode polarization. The other polarization mechanism observed at frequencies higher than 10 Hz may be dipolar [14].

When $GaAs_{1-x}Bi_x$ samples were investigated, it was shown that the dielectric constant of $GaAs_{1-x}Bi_x$ samples is greater than that of GaAs at frequencies lower than 10 Hz [15]. This may indicate the presence of larger number of free charge carriers in these structures. The dielectric constant decreased with increasing frequency for all $GaAs_{1-x}Bix$ samples.

The dielectric constants for 1 %, 2.5 % and 3.5 % $GaAs_{1-x}Bi_x$ at 100 kHz are 4.2, 4.4 and 4.7, respectively. At frequencies lower than 10 Hz it is shown that there is an increasing effect of increasing ratio of Bi component on dielectric constant [16, 17]. The slopes obtained from dielectric loss versus angular frequency graph seen in the inset of Fig. 1, give values between –0.7 and –0.85. In the literature, the slopes lower than –1 are attributed to electrode polarization at low frequencies. For frequencies higher than 10 Hz, it is shown that dipolar polarization becomes the prevailing mechanism [18]. Between 10 Hz and 10 kHz, the presence of Bi causes a sharp decrease of dielectric constant of $GaAs_{1-x}Bi_x$ in comparison to dielectric constant of GaAs. The exchange between As and Bi may increase the filling ratio because of the difference between atomic numbers. Thus, the presence of Bi may cause a decrease in the orientation ability of charge carriers. Besides, the dielectric constant of $GaAs_{1-x}Bi_x$ increases with increasing Bi ratio from 1 % to 3.5 %. The increasing ratio of Bi causes the production of positive charged holes. Thus, the ability of polarization increases [18, 19].

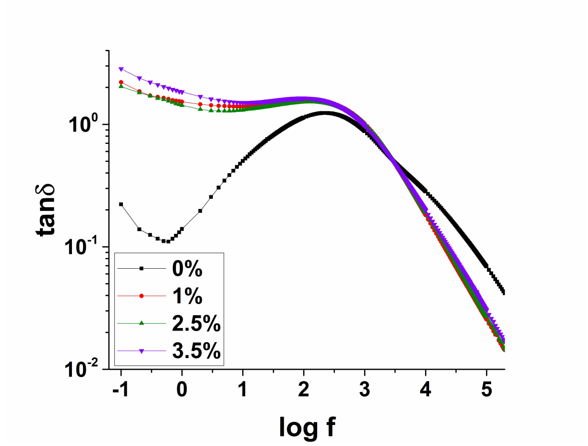

Fig. 2. Frequency dependence of tanδ at various Bi component ratios.

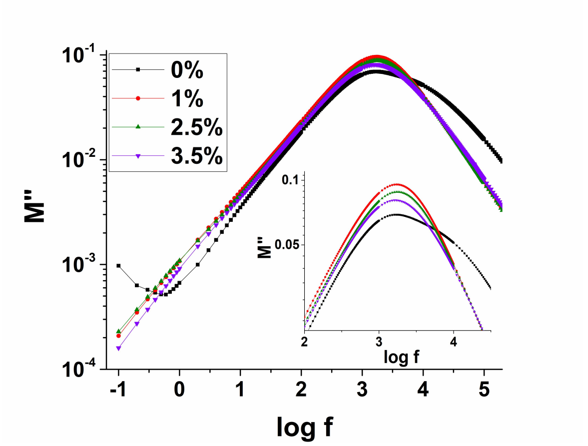

Fig. 3. Frequency dependence of imaginary electric modulus at various Bi component ratios.

The frequency dependence of tanδ is shown in Fig. 2. tanδ minima are observed at frequencies lower than 10 Hz. The tanδ minimum for GaAs is observed around 1 Hz. When the values of tanδ of GaAs and of $GaAs_{1-x}Bi_x$ are compared, tanδ minima of $GaAs_{1-x}Bi_x$ shift toward higher frequencies. Besides, tanδ values of $GaAs_{1-x}Bi_x$ are 10 times greater than that of GaAs. These minima may indicate the presence of electrode polarization. Shifting of tanδ minima toward higher frequencies with presence Bi component may show the effect of increasing charge carriers. Around 1 kHz, tanδ maxima are observed. These maxima may indicate the effect of dipolar polarization at these frequencies. At 1 kHz region the maxima shift toward low frequencies with increasing Bi content. The increase in the number of charge carriers may cause a decrease in orientation ability of dipoles [18, 20]. Also in Fig. 2 the presence of an additional polarization mechanism at frequencies higher than 10 kHz for GaAs is observed as a shoulder. This mechanism can be observed in Fig. 3 as a significant shoulder.

The frequency dependence of imaginary electric modulus is shown in Fig. 3. Imaginary electric modulus can be derived from dielectric constant and dielectric loss with equation 2:

$$M'' = \frac{\varepsilon_2}{\varepsilon_1^2 + \varepsilon_2^2} \qquad (2)$$

Electric modulus analysis is an alternative approach to explore electrical properties of a material and to magnify any other effects present in the sample unidentifiable or superimposed with dielectric constant and dielectric loss as a result of different relaxation time constants [13]. The modulus representation suppresses the unwanted effects of extrinsic relaxation often used in the analysis of dynamic conductivities of ionically conducting glasses. The advantage of adopting complex electric modulus spectra is that they can distinguish between electrode polarization and grain boundary conduction processes using electric modulus spectroscopic analysis [21]. At frequencies lower than 10 Hz, a minimum is observed for GaAs corresponding to frequency dependent tanδ minimum. But for $GaAs_{1-x}Bi_x$ samples, the minima corresponding to tanδ minima are not observed. This result is in accordance with low-frequency region in Fig. 2. There are peaks around 1 kHz. These peaks shift toward low frequencies with increasing Bi content. Low frequency side of these peaks indicates charge carriers contributing to conductivity with long-range displacement and the high-frequency side of these peaks indicates the short range displacement and polarization of these charge carriers [22]. It is shown that Bi presence causes an increase in the conductive character of the structure at low-frequency side.

Table 1. The relaxation times calculated in the low-frequency region.

Sample with component ratio [%]	Relaxation time [ms]
0	4.17
1	1.62
2.5	1.28
3.5	1.61

In Fig. 3 a shoulder-like mechanism for GaAs is detected at frequencies higher than 10 kHz. This mechanism may be caused by ionic polarization. However, for $GaAs_{1-x}Bi_x$ samples, this mechanism is not observed. This may indicate the decreasing polarization because of the increasing filling ratio due to the presence of Bi.

The relation between real electric modulus M' and imaginary electric modulus M'' for GaAs and $GaAs_{1-x}Bi_x$ with different ratio of Bi is shown in Fig. 4. For GaAs, two regions with different relaxation times are observed which is shown in the inset of Fig. 4. The relaxation times are calculated by using Cole-Cole semicircles. For $GaAs_{1-x}Bi_x$ samples there is one relaxation region. The calculated relaxation times in Table 1 are of the order of millisecond (ms).

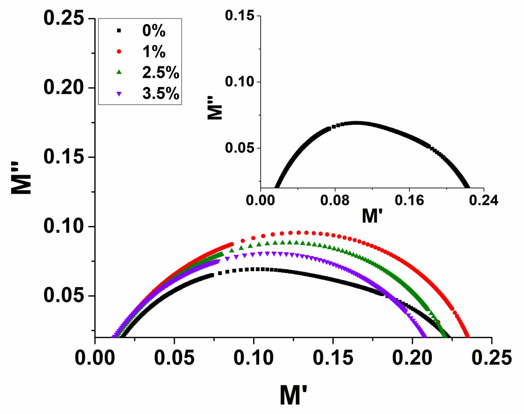

Fig. 4. Cole-Cole curves for electric modulus at various Bi component ratios.

The relaxation time for the high-frequency side of GaAs, which is shown in the inset of Fig. 4 as a shoulder on the right-hand side of the horizontal axis, has been calculated as 2.5 µs. When the arrangement of relaxation times is considered, the relaxation times of the order of ms and µs can be attributed to dipolar [23] and ionic polarizations [24], respectively. The sizes of semicircles become smaller with increasing Bi content. This decrease in the size of semicircle may be attributed to decreasing relaxation time with increasing Bi content [25, 26].

4. Conclusions

Dielectric properties of GaAs and Bi containing GaAs samples were compared depending on the ratio of Bi. The dielectric characterization results showed that GaAs exhibits two relaxation regions corresponding to dipolar polarization at low frequencies and ionic polarization at high frequencies in addition to space-charge polarization at the lowest frequencies while there was only one relaxation region corresponding to dipolar polarization for $GaAs_{1-x}Bi_x$ samples. This shows that Bi component may cause the ionic and space-charge polarizations to vanish due to new bonds and filling of the GaAs lattice structure, respectively. Thus, it is concluded that a dipolar polarization has an influence on the dielectric properties of $GaAs_{1-x}Bi_x$ in the investigated frequency range. These results support the results obtained from the study of optical properties of GaAs and $GaAs_{1-x}Bi_x$ presented in the literature.

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