ORIGINAL ARTICLE

Piezoelectric effects of single-crystal GaAs and multi-layered $Al_xGa_{1-x}As/GaAs$ material measured by the Michelson interferometer

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Abstract:

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The inverse piezoelectric effect, in which the strains were electrically induced, in a single crystal of GaAs and in a multilayer structure of $Al_xGa_{1-x}As/GaAs$ was measured using a simple optical system, i.e., Michelson interferometer. An ac driving voltage was applied to the sample to produce a change in the order of 10^{-13} m in sample thickness. These changes were detected by the optical system to give the sample displacement as a function of applied driving voltage. The slope of the plot of this relationship led to the piezoelectric coefficients of $(2.8\pm0.1)\times10^{-12}$ and $(3.9\pm0.1)\times10^{-12}$ m/V for GaAs and $Al_xGa_{1-x}As/GaAs$, respectively. The first agreed well with reported values and the latter was the first report for $Al_xGa_{1-x}As/GaAs$. Owing to the equality for the inverse effect and the direct effect, in which an electric field can be mechanically induced, it is anticipated that in the absence of external electric field, the internal piezoelectric field can be induced in the multi-layered semiconductor.

Key words : piezoelectric, interferometer, semiconductor

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บทคัดย่อ

ปัญญา แขน้ำแก้ว ศุภสโรช หมื่นสิทธิ์ และ ภัทร อัยรักษ์

ปรากฏการณ์ไพอิโซอิเล็กตริกที่วัดด้วยไมเคิลสันอินเทอร์เฟอร์โรมิเตอร์ของผลึกเดี่ยวแกลเลียมอาร์เซไนด์และวัสดุหลายชั้นของอลูมิเนียม-แกลเลียมอาร์เซไนด์ และของแกลเลียมอาร์เซไนด์

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ปรากฏการณ์ไพอิโซอิเล็กตริกแบบกลับซึ่งความเครียดถูกเหนี่ยวนำให้เกิดขึ้นได้ด้วยสนามไฟฟ้า ในผลึกเดี่ยวของแกลเลียมอาร์เซไนด์ (GaAs) และในโครงสร้างหลายชั้นของอลูมิเนียม-แกลเลียมอาร์เซไนด์และของแกลเลียมอาร์เซไนด์ ($Al_xGa_{1-x}As/GaAs$) ได้รับการตรวจวัดด้วยระบบทางแสงอย่างง่ายที่เรียกว่าไมเคิลสันอินเทอร์เฟอร์โรมิเตอร์ เมื่อศักย์ไฟฟ้ากระแสสลับถูกป้อนให้แก่สารตัวอย่างจะทำให้เกิดการเปลี่ยนแปลงในระดับ 10^{-13} เมตร ในแนวความหนาของตัวอย่าง การเปลี่ยนแปลงนี้ตรวจจับได้ด้วยระบบทางแสงข้างต้น ทำให้ได้การกระจัดของตัวอย่างเป็นฟังก์ชันกับศักย์ไฟฟ้าที่ป้อน ความชันของกราฟความสัมพันธ์นี้นำไปสู่ค่าคงที่ไพอิโซอิเล็กตริกเท่ากับ $(2.8\pm0.1)\times10^{-12}$ และ $(3.9\pm0.1)\times10^{-12}$ m/V สำหรับ GaAs และ $Al_xGa_{1-x}As/GaAs$ ตามลำดับ ค่าแรกสอดคล้องกับค่าที่เคยมีการรายงาน ค่าหลังเป็นการรายงานครั้งแรกสำหรับ $Al_xGa_{1-x}As/GaAs$ จากการมีความเท่าเทียมกันของปรากฏการณ์ไพอิโซอิเล็กตริกแบบกลับกับตรงซึ่งสนามไฟฟ้าถูกเหนี่ยวนำด้วยวิธีทางกล ทำให้คาดเดาได้ว่าแม้ปราศจากสนามไฟฟ้าภายนอก สนามไพอิโซอิเล็กตริกภายในก็สามารถเกิดขึ้นได้ในสารกึ่งตัวนำหลายชั้น

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A complete set of material parameters for semiconductors such as gallium arsenide (GaAs) and $Al_xGa_{1-x}As$ has been reviewed elsewhere (Blakemore, 1982; Adachi, 1985). Obviously, sets of theoretical values of the various piezoelectric coefficients for semiconducting materials have been reported whereas experimental values of the coefficients appear to be lacking. The present work made use of the inverse piezoelectric effect for measuring the coefficients, with the strain being measured by optical interferometry. By using this technique, the conductivity problems possibly caused by charge migration within a semiconductor could be avoided.

GaAs crystallizes in the zinc-blende structure, which is the simplest crystal lacking a center of symmetry and, hence, capable of exhibiting piezoelectric behaviour (Adachi, 1992). The piezoelectric tensor in zinc-blend crystal has the form:

$$d = \begin{vmatrix} 0 & 0 & 0 & d_{14} & 0 & 0 \\ 0 & 0 & 0 & 0 & d_{14} & 0 \\ 0 & 0 & 0 & 0 & 0 & d_{14} \end{vmatrix} \tag{1}$$

The only non-zero component, d_{14} is the piezoelectric strain coefficient which is connected with the piezoelectric coefficient obtained from a thickness expansion, d_{33} as (Mason, 1964)

$$d_{33} = \frac{d_{14}}{\sqrt{3}} \tag{2}$$

By applying an ac electric field across a thickness, the d_{33} value can be deduced from (Zhang *et al.*, 1988)

$$d_{33} = \frac{d_{ac}}{V} \tag{3}$$

where d_{ac} is the resulting field-induced mechanical displacement in the direction normal to the crystal plane and V is the applied driving voltage.

For $Al_xGa_{1-x}As$, which is most commonly prepared in a form of thin films grown on zinc-blend structure substrates, the material parameters, e.g., dielectric constant, ionization energy and piezoelectric coefficient, were calculated as a function of 'x' (Adachi, 1985). As this material is of importance for electron- and wave-device applications, accurate experimental measurements of the piezoelectric coefficient should have significant value.

Materials and Methods

The GaAs samples used in this work were cut into 4 mm × 4 mm from a 0.3 mm-thick commercial (111)B-n^+ wafer. The $Al_xGa_{1-x}As$/GaAs sample was prepared by the metalorganic chemical vapour deposition (MOCVD) (Shur, 1990). A sequence of the layers as shown in Table 1. As a check on the influence of the electrode material on the measured piezoelectric response, three different metals, namely aluminum (Al), gold (Au) and indium-gold (In-Au) were tested. Each of them was evaporated over an area of a diameter of 0.2 mm of the sample surface for using as electrical contacts. Electroded samples were checked for current-voltage (I-V) characteristics using the HP 4140B pA Meter/DC Voltage Source.

Table 1. Layer sequences of the $Al_xGa_{1-x}As$ sample.

Thickness ×(10^{-10} m)	Layer	x	Type
500	GaAs		n
2000	$Al_xGa_{1-x}As$	0.1	n
1000	$Al_xGa_{1-x}As$	0.3	
100	GaAs		
1000	$Al_xGa_{1-x}As$	0.3	
2000	$Al_xGa_{1-x}As$	0.3	p
3000	GaAs		p

In the Michelson interferometric arrangement (Muensit and Kheanumkeaw, 2002), the incoming laser from a Uniphase 1135P He-Ne laser source was divided into two beams by a beam splitter. One of the beams was reflected from a reference mirror mounted on a piezoelectric transducer and the other beam from the electrode on the free surface of the sample. The other surface of the sample was glued with conducting epoxy to a brass plate. An ac field was applied to the sample with electrical contacts arranged in a manner that the thickness excitation measurement (IEEE Standard on Piezoelectricity, 1988) could be performed. The reflected laser beams combined at the beam splitter and produced an interference pattern. A *pin* photodiode detector was used to detect the changes in light intensity of the interference pattern. The detector voltage was measured by a SR 530 Lock-in Amplifier (Stanford Research Systems) and converted into the displacement of the sample surface. At a constant driving frequency, the driving voltage was varied and measurement was repeated over the frequencies above 1 kHz.

Results and Discussion

A typical I-V curve was observed for GaAs with indium-gold as shown in Figure 1. The linear characteristic of the curve resulted from an ohmic contact between the metal and the sample surface (Sze, 1969). For the $Al_xGa_{1-x}As$/GaAs sample with indium-gold, a p-n junction characteristic was obtained. In the following measurements, indium-gold was chosen as the electrodes for all samples.

The interferometric measurements were repeatable over the frequency range from 5 kHz to 20 kHz for both GaAs (Figure 2) and $Al_xGa_{1-x}As$/GaAs (Figure 3). For each sample, a linear response was observed over the driving voltages ranged from 1 V to 10 V at a constant driving frequency. A minimum value of the sample displacement was in the order of 10^{-13} m. The slope of the plot for GaAs was $(1.6\pm0.1)\times10^{-12}$ m/V. From equation (2), the slope gave the d_{14} coefficient to be $(2.8\pm0.1)\times10^{-12}$ m/V. This value was about 5%

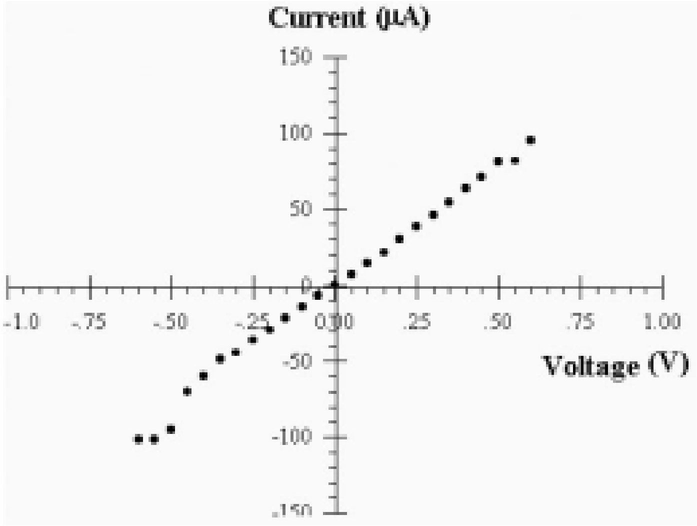

Figure 1. A typical I-V curve for GaAs with indium-gold electrode.

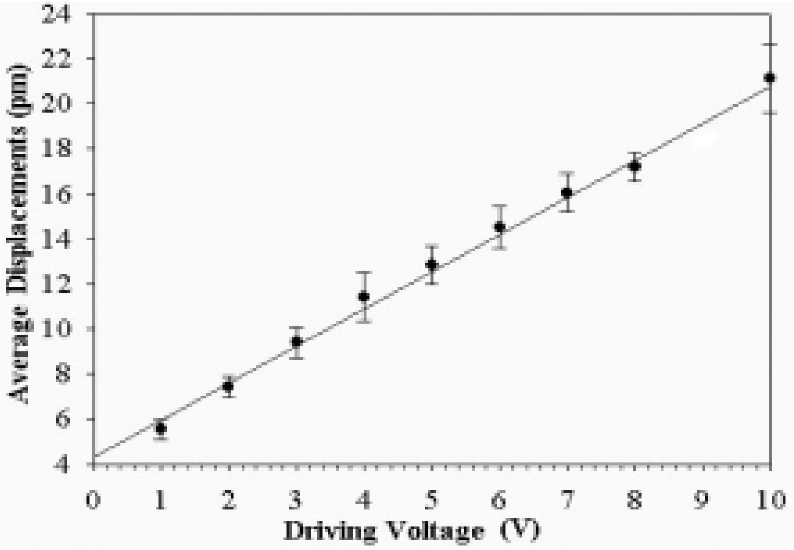

Figure 2. Avearage displacement over the frequencies ranged from 5 kHz to 20 kHz as a function of driving voltage for GaAs with indium-gold electrode.

different from the values reported in the literature (Charlson and Mott, 1963; Arlt and Quadflieg, 1968). The slope of the plot for $Al_xGa_{1-x}As/GaAs$ gave the d_{14} coefficient to be $(3.9\pm0.1)\times10^{-12}$ m/V.

A theoretical prediction of a value of the d_{14} coefficient for $Al_xGa_{1-x}As/GaAs$ (Adachi, 1985) is $d_{14}(x) = -2.69-1.13\,x$. By this equation, the measured d_{14} coefficient for $Al_xGa_{1-x}As/GaAs$ in this work corresponded with x = 0.98. It could be noticed that an addition of all of the x values in Table 1 was equal to 1.0, which was only 2% different from 0.98. Oviously, the observed piezoelectric response in the multilayer structure of $Al_xGa_{1-x}As/GaAs$ was not from any particular layer but averaged over all the layers.

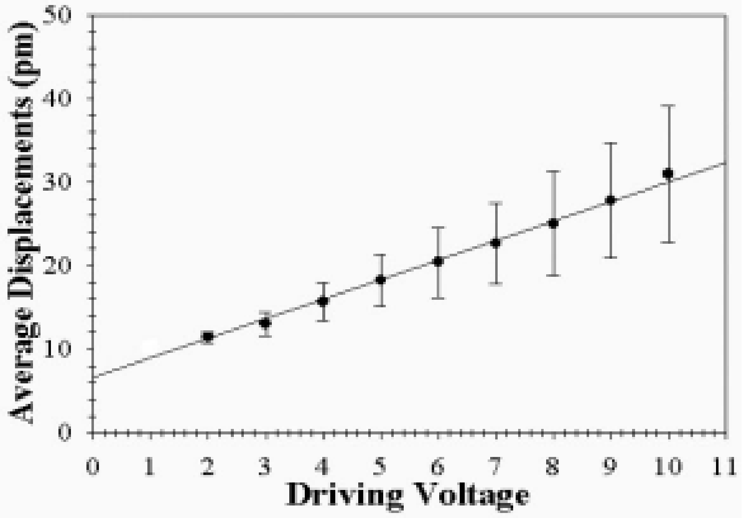

Figure 3. Avearage displacement over the frequencies ranged from 5 kHz to 20 kHz as a function of driving voltage for $Al_xGa_{1-x}As/GaAs$ with indium-gold electrode.

Conclusion

The Michelson-type interferometer was used in this work to measure the d_{14} coefficient for GaAs and an accurate value of the coefficient was obtained to be $(2.8\pm0.1)\times10^{-12}$ m/V. The technique was applied for investigating for the first time the piezoelectric effect in $Al_xGa_{1-x}As/GaAs$ and received a d_{14} value of $(3.9\pm0.1)\times10^{-12}$ m/V. By theoretical and experimental assessments, the multilayer structure sample showed the average piezoelectric response, which depended on the concentration of Al (or Ga) in the sample. Based on the direct piezoelectric effect, in which an electric field is induced by a strain, a similar response is anticipated to occur in this sample though an external electric field is zero. This is a consequence of the residual strains caused by some lattice constant mismatches in a structure with alternate layers of different materials (Bykhovski *et al.*, 1995; Smith, 1997; Rees, 1997). Therefore, the piezoelectric effect must be properly accounted for in the design of strain-layered devices. Making use of this effect in deliberately strained structures to produce devices with desirable properties is possible (Disseix *et al.*, 1999).

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