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Transverse acoustoelectric voltage measurements of GaAs grown directly on (100) Si substrates

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Transverse acoustoelectric voltage (TAV) measurements have been analyzed as a function of incident photon energy, dc bias voltage, temperature, and surface acoustic wave (SAW) frequency of GaAs layer ($\sim 1.4\,\mu$m thick) grown on a vicinal Si(100) substrate by molecular-beam epitaxy. The TAV technique is used to show that the band gap and impurity level transitions are of slightly lower energies, compared to the bulk GaAs. This might be due to the residual strain changes in the band structure of GaAs grown on Si. It is also noticed that the presence of an interface considerably changes the shape of the experimental TAV versus bias voltage at low temperatures. Drastic variations of TAV as a function of SAW frequency and temperature are also observed. The cause of variations is not yet clear, but possible explanations are discussed.

I. INTRODUCTION

The growth of GaAs on Si substrates is a promising technique for the future development of optoelectronic devices since Si is available as a relatively cheap, large area substrate with better thermal and mechanical properties than GaAs substrates. GaAs devices such as solar cells,[1] light-emitting diodes,[2] lasers,[3] and field-effect transistors[4,5] have been successfully fabricated on Si substrates.

While GaAs on Si has attracted considerable attention for device applications, the relatively large strain in GaAs grown directly on vicinal Si(001) wafers as measured, for example, by means of MeV ion channeling technique[6] represents a significant problem for device yield and reliability. The growth of GaAs layers exhibits tensile strain in the plane parallel to the GaAs/Si interface due the thermal expansion coefficient difference of GaAs compared to Si.[7] The samples [Sample 1: GaAs(n)/Si(p), Sample 2: GaAs(n)/Si(n)] used for TAV measurement have epitaxial layers grown directly on ⟨100⟩ silicon substrates by molecular-beam epitaxy (MBE). The details of the preparation and growth procedure can be found elsewhere.[8]

Photoluminescence spectra of GaAs/Si are reported in Refs. 10–14. The TAV spectroscopy is similar to the photoconductivity spectroscopy. In this paper, a GaAs layer grown on Si substrate is characterized by using the transverse acoustoelectric voltage (TAV) measurements. Acoustoelectric voltage develops due to nonlinear interaction between the electric field accompanying SAW and the free carriers of the semiconductor. TAV amplitude is proportional to the net conductivity difference, i.e., TAV $\propto n\mu_n - p\mu_p$. However, the TAV signal is negative for p-type surface conductivity and positive for n-type surface conductivity. The effect of temperature on the TAV amplitude and the field-effect measurements (i.e., TAV-V_b) are discussed elsewhere.[14,15] As the temperature is changed, the Fermi level changes as a result of the temperature dependence of the free energy of the impurity levels, the semiconductor band-gap energy, and the effective density of states. The dc bias field is applied to the surface of the semiconductor in Fig. 1. An aluminum layer of approximately 2000 Å thickness is deposited at the surface of the delay line. This aluminum layer is used as a gate to change the surface potential of the semiconductor. By changing the bias voltage, the carrier concentration over the interaction window is effectively modulated and TAV as a function of applied bias voltage is obtained. The interface trap density versus interface trap energy can be determined by comparing the experimental TAV-V_b with the theoretical TAV versus surface poten-

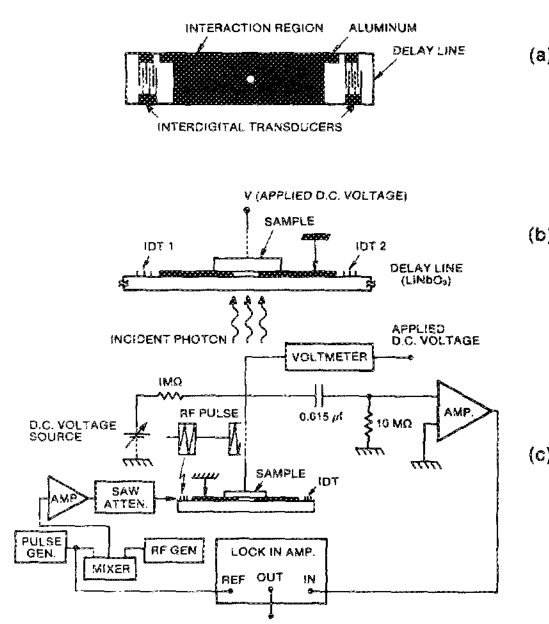

FIG. 1. Experimental setup for TAV measurements.

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tial curves. This procedure is similar to the high-frequency capacitance versus voltage (C-V) technique.[16]

The TAV measurements are made without any electrical contacts and the measurement is localized to a small region of the wafer. One can envision automated equipment, using this SAW technique, which can measure electrical properties such as lifetime, surface generation velocity, etc., all over the wafer. TAV measurements also yield mobilities in perpendicular directions.[17] Hence, these measurements can be used to study the electron mobilities of GaAs grown on Si and of a two-dimensional electron system in superlattices. In characterizing microstructural systems, it would be desirable to obtain as much information as possible from simple measurements. We report on TAV oscillations as a function of SAW frequency and temperature in the GaAs/Si systems (sample 2). The origin of the variations that have been observed[18,19] is unclear, but speculations have included the induced acoustoelectric effect in the GaAs layer. Although such an explanation might be physically sound, the question of other possible contributions to the effect remains open.

II. EXPERIMENTAL RESULTS AND DISCUSSION

The experimental arrangment is shown in Fig. 1. The semiconductor is placed at the surface of a highly polished $LiNbO_3$ substrate where surface acoustic waves are generated. An rf pulse (~ 1 ms duration) with center frequency of 55 MHz is applied to the interdigital transducer [Fig. 1(a)] to launch the surface waves. The TAV is detected across the semiconductor and it is monitored while changing the wavelength of the incident photons [Fig. 1(b)]. A high-resolution (5 Å) Jobin–Yvon HRS 2 monochromator is used to obtain the TAV spectrum. The experiments are performed both at room temperature and at low temperatures. The illumination is directed at the surface of the GaAs layer where the nonlinear interaction between the electric field of the SAW and the semiconductor free carriers takes place. In TAV versus bias voltage experiments, the delay line shown in Fig. 1(c) is used; an aluminum path with interaction window is fabricated on the $LiNbO_3$ substrate. The interaction window and the interdigital transducers are all fabricated using standard evaporation and photolithography techniques.

TAV spectra are detected for the GaAs layer on Si substrate (sample No. 1) at room temperature and 83 K. Figure 2(a) shows TAV versus photon energy (E_{ph}) at room temperature. The onset of TAV amplitude, which is at 1.418 eV, corresponds to band-to-band transition. The TAV spectrum for bulk GaAs (Cr doped) as shown in Fig. 2(b) is detected and shows the band-to-band transition at 1.424 eV. Figures 3(a) and 3(b) show the TAV spectra at 83 K of both GaAs/Si and bulk GaAs. A sharp absorption peak is observed at 1.499 eV for bulk GaAs as shown in Fig. 3(b). This peak is due to a defect related transition. Figure 3(a) shows the weak absorption peak at 1.490 eV. The amplitude of the TAV absorption peak is very weak indicating a short nonradiative lifetime in the GaAs layer on Si (the deep states at the interface can account for significantly reducing the overall

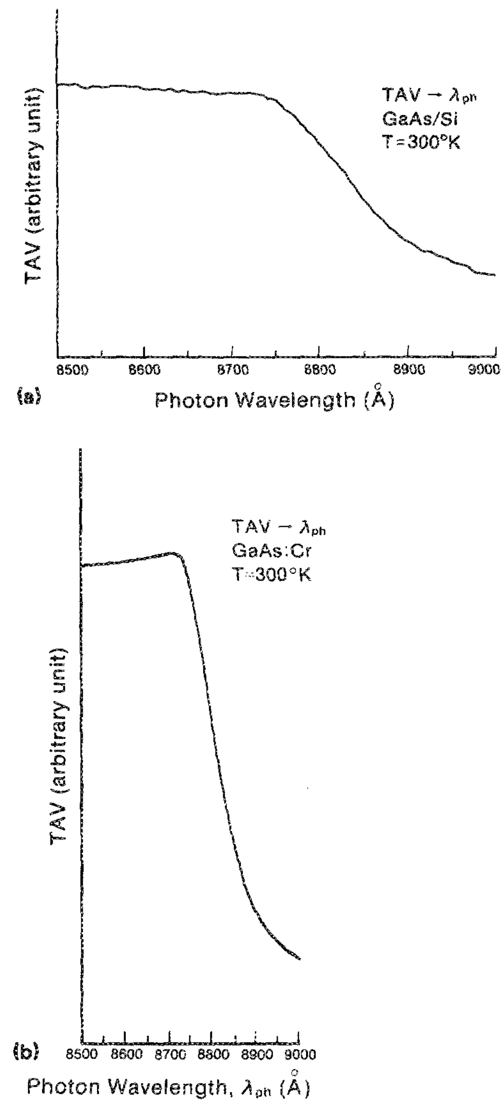

FIG. 2. TAV vs λ_{ph} at room temperature for (a) GaAs/Si heterostructure, and (b) bulk GaAs.

TAV amplitude). This effect is explained later in connection with bias voltage measurement. The peak energy shift of a defect related and band-to-band transitions may be due to tensile stress, which is caused by the difference between the thermal expansion coefficients of GaAs and Si.

Figure 4 shows the TAV versus applied bias voltage at the surface of the GaAs layer at room temperature. The polarity of TAV is positive at zero bias voltage, indicating that the effective surface carrier conductivity is n type. The TAV amplitude changes with different bias voltage. At positive biases, TAV is almost constant; this is known as the accumulation region. As the surface is depleted via negative bias voltages, the TAV amplitude changes due to less accumulation and eventual depletion of electrons. No inversion occurs in this structure.

Figure 5 shows TAV versus V_b (bias voltage) at different temperatures (sample 2). A structure is observed at low temperatures, which is very clear as compared to behavior at higher temperatures. We believe that this might be due to a deep level which is not observed at room temperature due to

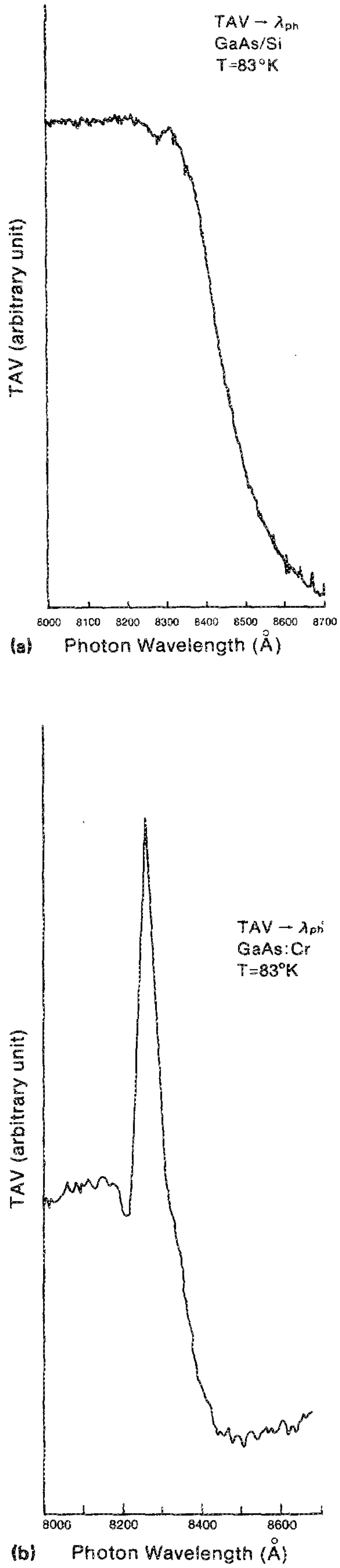

FIG. 3. TAV vs λ_{ph} at 83 K for (a) GaAs/Si heterostructures and (b) bulk GaAs.

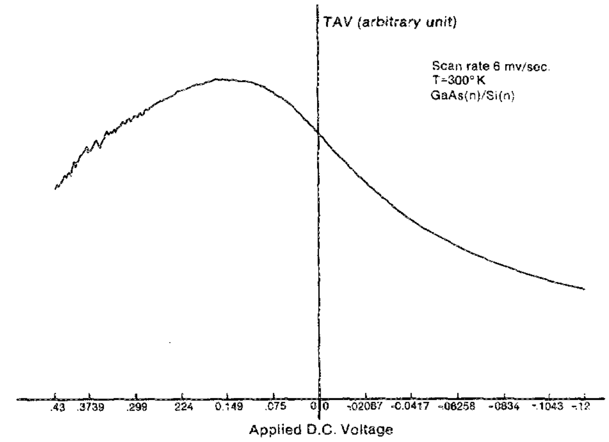

FIG. 4. TAV vs V_b (bias voltage) measurement at room temperature for GaAs/Si heterostructures.

emptying of the levels. At low temperature, this level is filled with electrons and the applied voltage tries to empty the trap levels thereby increasing the free-carrier concentration in the conduction band. This, in effect, increases the TAV amplitude. It is also noticed that the position of the structure shifts at different temperatures. The overall TAV amplitude at higher temperature increases due to higher electron concentrations.

A study is made using TAV vs f_{SAW} measurements to get a better understanding of this interesting material system with respect to GaAs/AlAs superlattices.[18] Drastic variation of TAV as a function of SAW frequency is detected without polarity changes (i.e., $+ve$ to $-ve$ polarity of TAV amplitude). The magnitude of TAV as a function of SAW frequency changes with applied dc voltage at the GaAs layer as shown in Figs. 6 (a)–6(e). TAV amplitude almost vanishes for a bias voltage of around -0.72 V [see Fig. 6(e)]. It is interesting to compare the results with that obtained for a GaAs-AlGaAs superlattice[19] which exhibits a

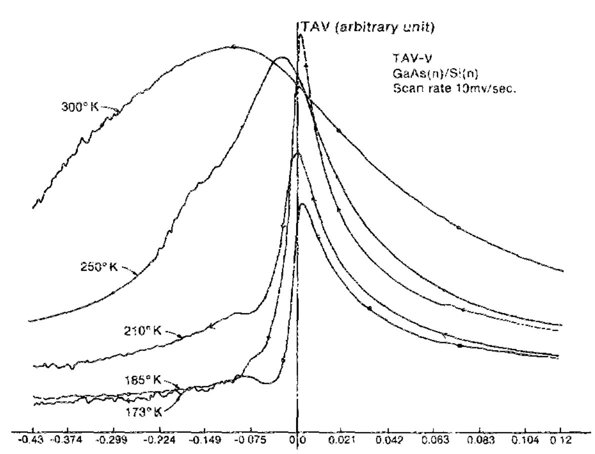

FIG. 5. TAV vs V_b measurements at different temperatures for GaAs/Si heterostructures.

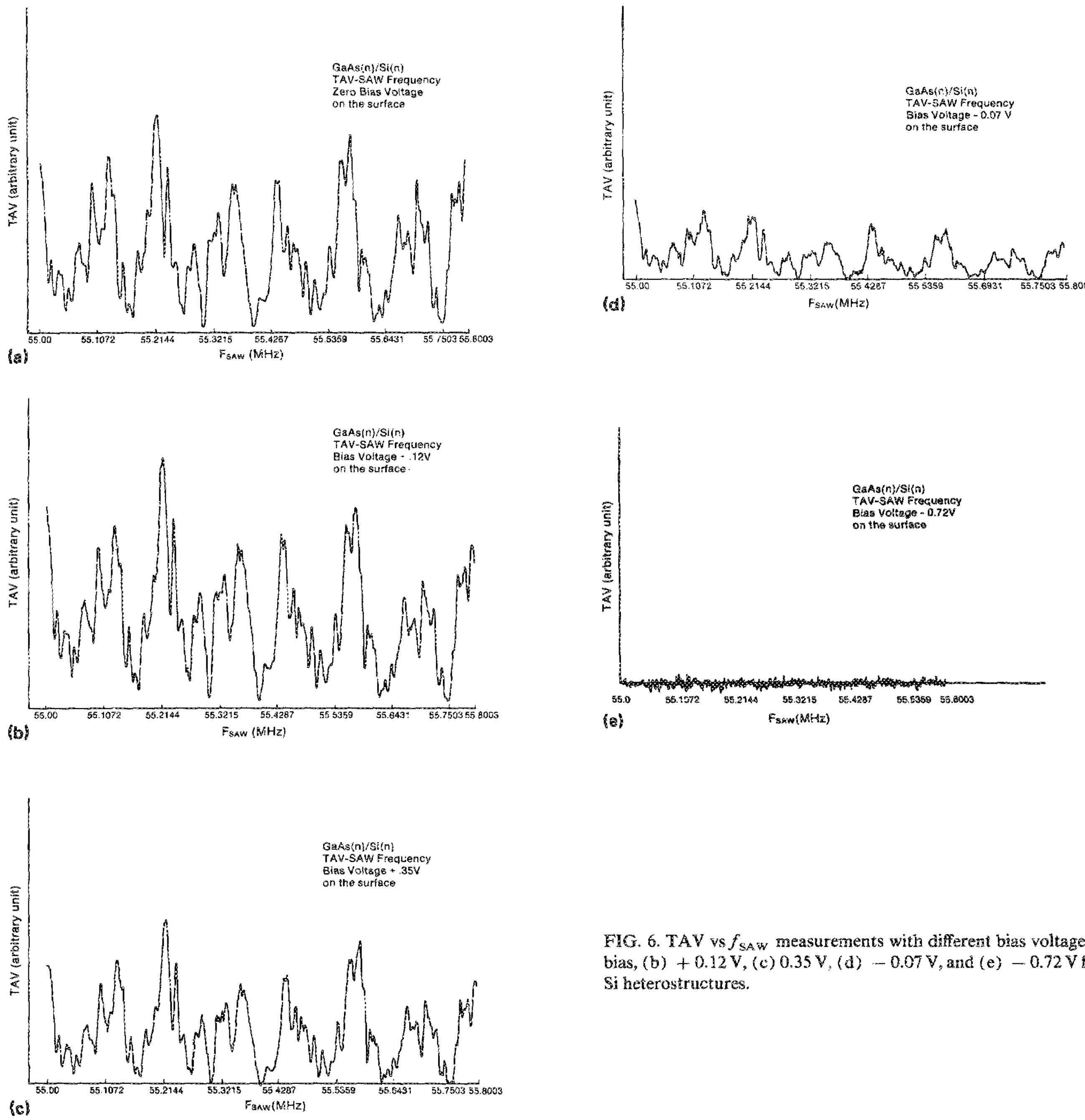

FIG. 6. TAV vs f_{SAW} measurements with different bias voltage, (a) zero bias, (b) $+0.12$ V, (c) 0.35 V, (d) -0.07 V, and (e) -0.72 V for GaAs/Si heterostructures.

drastic variation as a function of SAW frequency and the polarity of TAV changes from $+ve$ to $-ve$.

Figure 7 shows the TAV versus temperature of sample No. 2. The TAV of the heterostructure exhibits drastic variation and its absolute magnitude decreases as the temperature is decreased. On the other hand, TAV of the superlattice exhibits variation between $+ve$ and $-ve$ and its magnitude decreases as the temperature decreases as shown in Ref. 18. As can be seen in Figs. 6 and 7, the TAV of the heterostructure under these circumstances drastically changes as a function of SAW frequency and temperature, but the variation of TAV in bulk GaAs is very small.[18,19]

The explanation for the dramatic changes in the acoustoelectric voltages as a function of SAW frequency and tem-

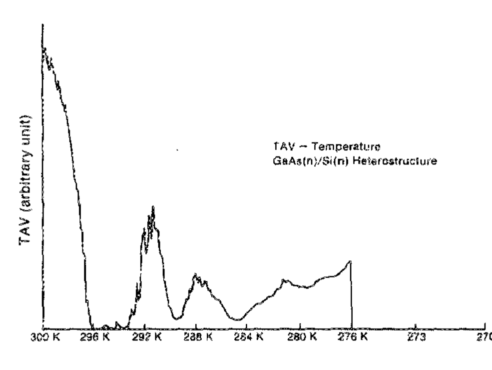

FIG. 7. TAV vs temperature measurements for GaAs/Si heterostructures.

perature is due to the composite structure.[18] We believe that the induced elastic wave in the GaAs layer can generate acoustoelectric voltage across the Si substrate. However, no quantitative analysis has been performed. It is therefore timely to consider also an analysis of the growth of elastic waves via the piezoelectric interaction in heterostructures. Broadly speaking, we can mention that the superlattices and GaAs/Si heterostructures are not very different as far as acoustoelectric variations are concerned.

III. CONCLUSIONS

In conclusion, we have presented a study of nondestructive TAV features from GaAs/Si heterostructures (sample No. 1) associated with band-to-band and band-to-impurity level transitions. It has been observed that band-to-band and band-to-impurity level transitions are of slightly lower energies compared to bulk GaAs. These features are due to changes in the band structure of GaAs grown on Si substrate resulting from the residual strain. We have also detected deep levels spatially localized near the GaAs and Si interface (sample No. 2). We have observed the dramatic variations of TAV as a function of SAW frequency. This might be due to the acoustoelectric effect in this material system.

The GaAs/Si structure studied in this work exhibits a number of interesting properties in its TAV. There is no inversion region in the TAV curve. There is a region of the TAV curve near zero bias which displays a small structure when studied in low temperature. This behavior is explained by the presence of deep levels localized near the GaAs/Si interface.

Finally, we present results concerning the crystal qualtiy of the GaAs layer grown on Si with respect to the optical properties by measuring and comparing the TAV amplitudes of GaAs/Si and homogeneous GaAs. The experimental data at both room and low temperatures are promising for further improvements in the crystal quality of GaAs epitaxial layers grown on Si substrates.

It is clear that any assertion regarding an acoustoelectric origin for the variations that we observe must be tentative until substantially more experimental evidence is forthcoming, and substantially more theoretical work is carried out on this topic.

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