A Technique for Profiling the Epilayer Channel of Surface Acoustic Wave Devices on Piezoelectric Semiconductors

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Abstract—A new method for determining the impurity doping profile of the transport epitaxial layer channel of surface acoustic wave devices on piezoelectric semiconductors is presented. This technique utilizes the same structure already present in these devices; thus, testing can be done without altering or damaging the device. Another advantage of this technique over the equivalent *C–V* measurement is the high sensitivity of the TAV to higher resistivity materials.

Experiments and estimated doping profiles are presented along with the theoretical analysis of the measurement.

I. INTRODUCTION

SURFACE Acoustic Wave (SAW) devices on piezoelectric semiconductors have been developed for a variety of high-speed analog signal processing applications such as transversal filters, convolvers, and correlators. Piezoelectric semiconductors such as GaAs, InP, and InSb are used to generate and propagate the SAW. These devices are basically tapped delay lines, with each tap connected to a common input or output line [1]. The delay is represented by the time necessary for the SAW to propagate on the surface of the semiconductor from the input to the output section of the device. The basic configuration of a SAW-based semiconductor delay line is represented in Fig. 1. The SAW is generated by applying a radio-frequency (RF) electric voltage across the input interdigital transducer (IDT); once generated, the acoustic wave propagates on the semiconductor surface toward the output IDT where part of the mechanical energy is transformed into electromagnetic energy and detected as an output voltage.

To improve the generation and propagation of the SAW, usually a (100) n-type GaAs epitaxial layer (epilayer), with thickness depending on the SAW wavelength, is grown by molecular beam epitaxy (MBE) or metal organic chemical vapor deposition (MOCVD) on top of the semi-insulating (SI) GaAs substrate. The energy of the

SAW is mainly contained in this layer; for this reason, it is also commonly called the transport channel.

An acoustic charge transport (ACT) device is a particular type of acoustic device in which an externally injected charge is transported by the electrical potential associated with the propagating SAW [2]. The electric charge, injected in the epilayer through an ohmic contact, in each instant is confined vertically by a combination of the depletion potential and SAW potential [3].

In order for these devices to function correctly, the transport channel must be depleted of mobile charges prior to the injection from the input contact [4]. Depletion of the epilayer is usually obtained using a reverse biased Schottky electrode above the channel (Fig. 1) along with a backgating bias which is applied to the SI substrate. The size and shape of the depleted region is determined by the applied voltage and the doping impurity profile present. The complete depletion of the epilayer is of great importance for the performance of these devices, and thus it is essential that we evaluate the electrical properties of the transport channel, in particular, the doping impurity profile [5]. In the following, the substrate ohmic contact was connected to ground, in order to avoid depletion from the back contact.

Investigation of doping profiles in semiconductors is mostly performed by capacitance–voltage (*C–V*) techniques such as pulsed *C–V*, feedback method, or second harmonic generation [6], [7]. The common characteristic of these measurements is that the depletion width (*w*) is monitored as a function of the applied bias voltage (*V*) by measuring the depletion capacitance (*C*). The analysis of the capacitance versus bias voltage relationship is conveniently done using the depletion-layer approximation in which the semiconductor is assumed to be divided into two distinct regions: 1) a layer that is entirely depleted of charge carriers; and 2) a deeper region of perfect charge neutrality. In this model, the transition between the two regions is abrupt; a more accurate interpretation of the *C–V* data would result in a considerably more difficult calculation because of the nonlinear relations involved. A correction to the value obtained for the carrier concentration is thus used to evaluate the impurity doping profile.

Generally, the application of capacitance methods to Schottky structures on SI semiconductors is considered
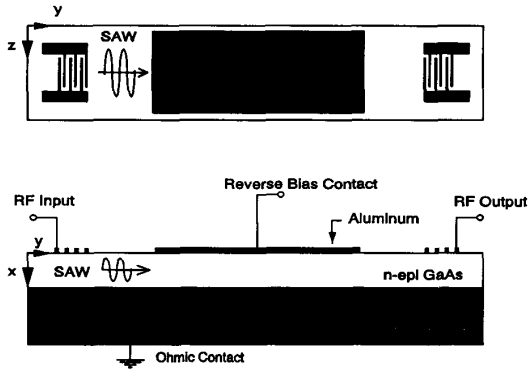
Fig. 1. Basic configuration of a SAW-based semiconductor delay line.

not feasible [8]. It is agreed, for instance, that the value of series resistance of the base region is too high, and this makes the C-V measurement difficult or even impossible [9].

We present a procedure to evaluate the free carriers and doping profile of the epilayer on the SI substrate, using the voltage generated across the semiconductor as a result of the nonlinear interaction of the free carriers with the electric field associated with the propagation of the SAW. This voltage, called transverse acoustoelectric voltage (TAV), is detected from the metal Schottky contact when the SAW propagates beneath it [10]. The TAV is a function of the free carrier concentration; therefore, in our experiments, we directly determine the majority carrier concentration (n) as a function of the reverse bias V. The depletion layer depth (w) is also evaluated from the mathematical analysis of the $n(V)$ curve.

For the device structure presented in this paper, it was not possible to perform C-V measurements; this was due to the presence of the semiinsulating GaAs substrate. The proposed technique can thus be utilized to complement C-V measurements in samples with resistivity in the 10^5–10^7 $\Omega \cdot$ cm range.

Nevertheless, comparison between C-V and TAV-V measurements has been extensively reported elsewhere on different samples. In particular, the equivalence of C-V and TAV-V measurements has been evaluated for semiconductor/insulator structures such as Si/SiO_2 and GaAs with thermal oxide [11], [12]. The doping profile of phosphorous implanted Si samples measured using TAV-V was also confirmed using spreading resistance measurements [13].

In reported measurements, the SAW was generated on a piezoelectric crystal such as $LiNbO_3$ and the samples to be characterized were placed in close proximity [14]. The technique presented utilizes the device structure already present in SAW devices, and testing can be done without altering or damaging the device.

The theoretical analysis of the proposed method is presented along with the estimated profile for one of the samples.

II. THEORETICAL ANALYSIS

The SAW propagation in piezoelectric semiconductors has been extensively discussed elsewhere [15]–[17]. Briefly, the acoustic propagation equations are solved together with the continuity, transport, and Poisson's equations [18]. From numerical calculations, it is found that the TAV amplitude is a function of the electron concentration at the surface or at the edge of the depletion layer, if one is present. A plot of the TAV versus electron concentration n is shown in Fig. 2. As can be easily observed, the TAV has an optimal range of n values. The reason is that for very low carrier concentration, the interaction between the electric field and the free carriers is weak, and the TAV amplitude is small; while for high values of n, the SAW electric field is screened by the high density of charges, thus again resulting in a small TAV amplitude. It is also to be noted that the TAV signal can be detected also for low carrier concentration materials and thus, for this reason, it is suitable for characterizing samples with values of resistivity ranging from 10 to 10^7 $\Omega \cdot$ cm. In the following, we will assume an n-type semiconductor, but the same considerations apply both for n and p-type materials.

Experimentally, the TAV is monitored as a function of the applied bias voltage. The data are then compared to the theoretical TAV-n curve. From the variation of the effective electron density versus the applied bias, the depletion depth w is evaluated numerically by proper analysis.

The spatial distribution of majority free carriers is assumed to be given by

$$n(x) \simeq 0 \qquad \text{for } x < w \qquad (1a)$$

$$n(x) = n_o(x) \qquad \text{for } x > w \qquad (1b)$$

where x is the distance from the surface (cm), $n_o(x)$ represents the electron distribution for $x > w$. Equations (1a) and (1b) imply an abrupt space edge approximation (ASCE) but do not involve the identification of $n(x)$ and $N_D(x)$ in the quasi-neutral region [19], [20]. Poisson's equation is considered along the depleted region:

$$\frac{d^2\phi(x)}{dx^2} = -\frac{q}{\epsilon_s} \cdot [N_D(x) - n(x)] \qquad (2)$$

where $\phi(x)$ is the electric potential (volts); q is the electronic charge $= 1.6 \times 10^{-19}$ C; and ϵ_s is semiconductor permittivity (F/cm).

The boundary conditions at w and at the surface ($x = 0$) are

$$\phi(w) = 0 \quad \text{and} \quad \phi(0) = \Psi_s \qquad (3)$$

$$E(w) = -\frac{d\phi(x)}{dx}\bigg|_{x=w} = 0 \qquad (4)$$

where Ψ_s is the surface potential (eV) relative to the bulk, and $E(w)$ is the electric field at w (V/cm).

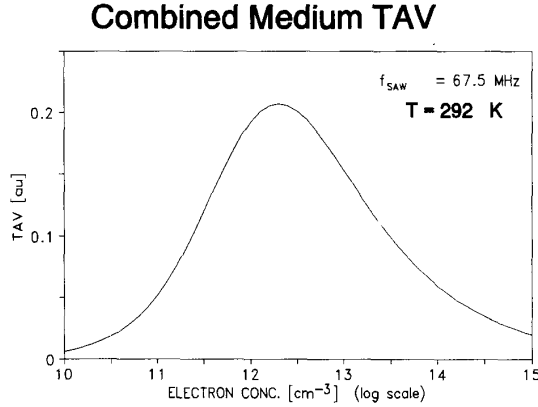The applied voltage (V) can be written in the following

Combined Medium TAV

Fig. 2. Calculated TAV amplitude as a function of free electron concentration.

Fig. 3. Flow chart of the impurity doping profile procedure using TAV-V measurements.

form:

$$V = V_{FB} + \Psi_s \qquad (5)$$

where V_{FB} is the flat-band voltage.

Considering the boundary conditions of (2)–(4), the applied voltage can be expressed as a function of the charge distribution by double integration

$$V - V_{FB} = \frac{q}{\epsilon_s} \cdot \int_0^w \int_w^{\zeta} [N_D(x) - n(x)] \, dx \, d\zeta. \qquad (6)$$

This equation is valid for any doping profile, and it is solved numerically using finite difference methods. After proper analytical manipulation and using the ASCE approximation (1), the variation in depletion width is related to the change in applied potential and to the carrier concentration by

$$(\Delta w(m))^2 + 2w(m - 1) \cdot \Delta w(m)$$

$$- 2\frac{\epsilon_s}{q \cdot n_o(m)} \cdot \Delta V_B(m) = 0 \qquad (7)$$

where $\Delta w(m)$ is the mth depletion width increment and

$$w(m - 1) = \sum_{n=1}^{m-1} \Delta w(n), \qquad \text{for } m \geq 2 \text{ and } w(0) = 0.$$

$$(8)$$

$\Delta w(m)$ and thus $w(m)$ are calculated using the value of $n_o(m)$ obtained from the TAV-V curve. The voltage increment ΔV can be chosen arbitrarily small (within experimental limits) for a more accurate calculation of the depletion width. In deriving equations (7) and (8), it was implicitly assumed that at the bias voltage equal to the flat band voltage ($V = V_{FB}$), the depletion layer width is zero.

Finally, the impurity doping concentration is calculated using the same reasoning as in C-V measurements. For the balance of drift and diffusion components, we obtain
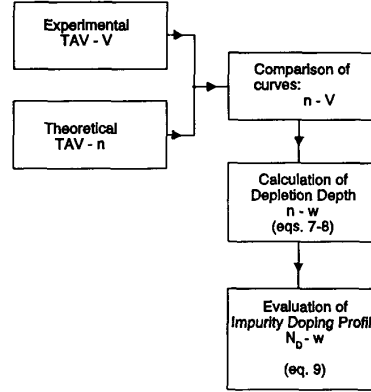
the following relationship [21]:

$$N_D(x) = n_o(x) - \left(\frac{kT}{q}\right)\left(\frac{\epsilon_s}{q}\right) \cdot \frac{d}{dx}\left[\frac{1}{n_o(x)} \cdot \frac{dn_o(x)}{dx}\right]. \qquad (9)$$

The flow chart of the depth profiling procedure using TAV-V measurements is shown in Fig. 3. Briefly, the experimental TAV-V experimental curve is compared to the theoretical plot of the TAV versus free carrier concentration to obtain the $n(V)$ curve. Using (7) and (8), the depletion width as a function of the applied bias is numerically calculated. The free carrier depth distribution is thus obtained, and finally the impurity doping profile is calculated using (9).

More accurate numerical procedures have been presented to improve the accuracy of the C-V profiling measurement [22]–[24], and all these methods can be incorporated in our technique.

III. RESULTS AND DISCUSSION

The schematic representation of the commonly utilized experimental arrangement is shown in Fig. 4. The SAW is generated by applying a 10-V peak-to-peak radio-frequency voltage to the IDT; the mechanical stress propagating on the surface is accompanied by an electric field generated by the piezoelectricity of the material [25]. The SAW propagates along the surface of the semiconductor creating stress variations which decay very rapidly with depth in the material. If the SAW passes under an identical IDT, an RF voltage is generated across the transducer, which thus acts as a delay line.

The device structure under study was fabricated on a n-type GaAs epilayer ($\simeq$ 8 μm thick) grown by the MOCVD process. The undoped liquid encapsulated Czochralski (LEC) SI GaAs was used as a substrate. The epilayer was not intentionally doped, but an electron concentration of approximately $3 \cdot 10^{14}$ cm^{-3} was measured by the manufacturers. The Al-Cr Schottky barrier metallization was used to form the IDT's and Schottky contacts by the metal liftoff technique.
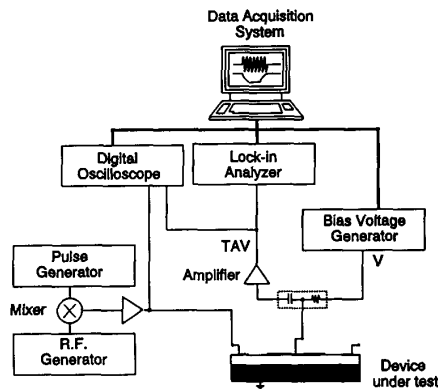
Fig. 4. Schematic representation of the experimental setup used for TAV-V measurements.
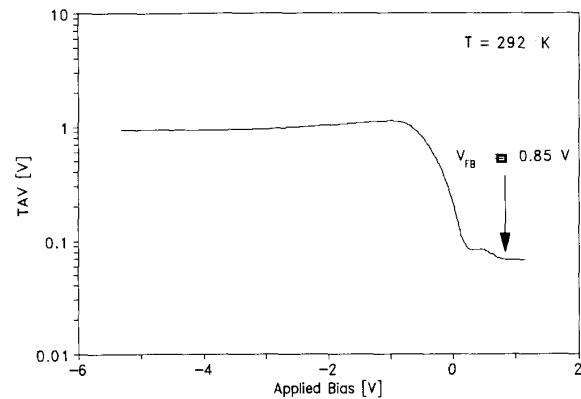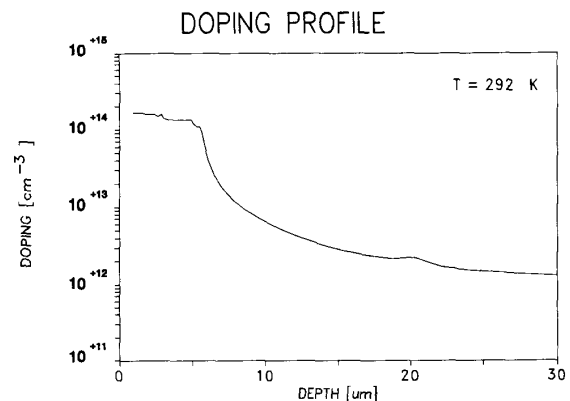
Fig. 5. TAV-V experimental curve.

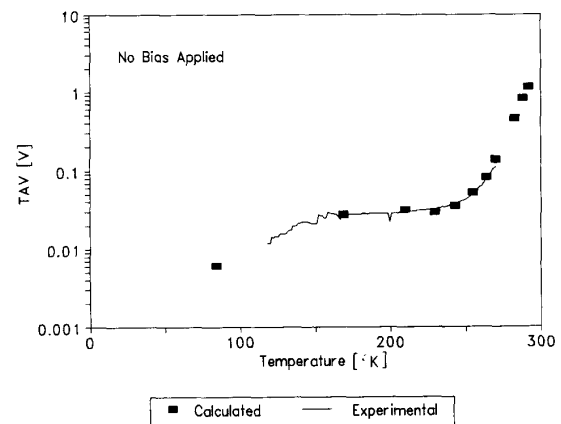Fig. 6. Impurity doping profile obtained using TAV-V measurements.

Fig. 7. Plot of the TAV versus temperature. The filled squares (■) represent the calculated values of TAV obtained using TAV-V data measured at different *T*. The solid line represents a direct experimental measurement of TAV-T.

The experimental TAV-V plot is shown in Fig. 5; to enhance the detection of the signal, a lock-in amplifier is used. At room temperature, the amplitude of the TAV is approximately 1 V. The flat-band voltage is measured as the applied voltage for which the TAV signal disappears. This is because the onset of a forward current in the Schottky diode completely overwhelms the nonlinear current which generates the TAV. Even though the TAV completely disappeared at an applied voltage of 0.85 V, the output of the lock-in amplifier still showed a nonzero value (Fig. 5). For our purposes, the TAV is practically zero for $V > V_{FB}$, and it is not constant in the reverse bias regime. Using the procedure presented in this paper, the impurity doping profile of Fig. 6 was obtained. It can be easily seen that the device has nominal N_D only to a depth of 6 μm. This result was somewhat expected; the degradation of the doping profile near the epilayer/SI GaAs interface was previously measured in this type of device [5]. In the case presented in [5], *C-V* measurements were performed and the doping concentration of the epilayer was higher ($\approx 10^{15}$ cm^{-3}), but nevertheless the effective depth of the layer was approximately 2 μm less than the nominal value.

Since we were not able to successfully perform *C-V* measurements on our samples, we envisioned another experiment to verify our results. The TAV versus bias voltage measurement was performed at different sample temperatures, ranging from room temperature to 84 K. For each curve, the doping profile was calculated; the effective electron concentration for a space-charge depth relative to zero applied bias was used to numerically evaluate the amplitude of the TAV signal for zero bias at each temperature. A discussion of the calculations involved will be published elsewhere [26].

The calculated values of the TAV amplitude as a function of temperature are plotted in Fig. 7 as filled squares. We have also experimentally measured the variation of the TAV amplitude as a function of sample temperature with zero applied bias. The experimental TAV-T curve is shown in Fig. 7 as a solid line.

It has to be emphasized that the calculated values of the TAV were obtained from a different and separate experiment, not from the TAV versus temperature plot. The values of the TAV amplitude were calculated by a different
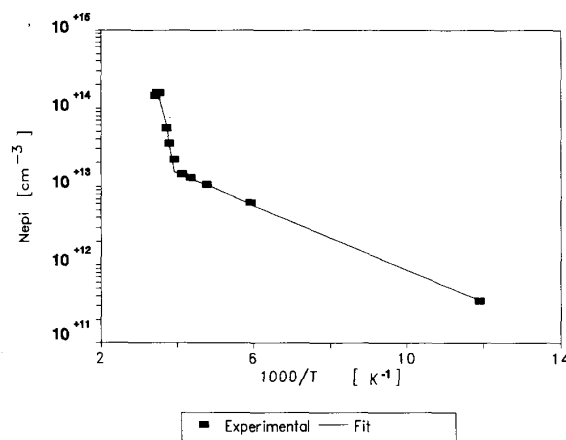
Fig. 8. Electron carrier concentration in the epilayer versus temperature. The filled squares (■) represent the values calculated using the TAV-V data at different T. The solid line represents the fit obtained assuming three different impurity levels.

computer program which used as input only the value of carrier concentration at the edge of the space-charge region. For each temperature, a plot analogous to the one shown in Fig. 2 can be calculated.

The agreement between the two curves is good, and this can be seen as an indication of the validity of the proposed procedure. Unfortunately, due to the presence of a thick SI GaAs substrate ($\approx$ 500 μm thick), we were not successful in measuring C-V curves.

From the data presented, we also extracted the free electron density in the epilayer at different temperatures. The calculated values for N_{epi} as a function of T are shown in Fig. 8 as filled squares. The solid line in the same figure represents a fit computed assuming three impurity levels with activation energies of 0.03, 0.19, and 0.4 eV. The relative densities are 4×10^{11}, 1.4×10^{13}, and 3×10^{14} cm^{-3}, respectively. The rapid decrease in concentration when cooling from 300 to 80 K was also reported in Hall measurements performed on GaAs epilayers grown on SI GaAs, and it has been suggested to be related to carrier freeze out of the 30 meV impurity level [27]. This energy level has been associated to the presence of Te in the growth system [28].

The impurity level with activation energy of 0.19 eV is probably identical with the level EL 14 seen in bulk material and in Te-doped MOVPE grown GaAs [29]: thus, we can conclude that it is also related to the presence of Te contamination in the growth system.

IV. CONCLUSIONS

In order to have a fully depleted transport channel, it is important to know its doping profile. This condition is vital for the correct functioning of SAW devices on piezoelectric semiconductors and, in particular, for ACT

devices. Furthermore, this information can be used to theoretically evaluate the performance of such devices [30].

The applicability of the TAV-V measurement for impurity profiling is demonstrated. Fundamental differences between the proposed method and the C-V technique are discussed, and the numerical analysis required to obtain the $n(w)$ curve is described. Limitations of the technique and the provision for further improvements are also discussed.

The main advantages of this technique over equivalent C-V measurements are the high sensitivity of the TAV to higher resistivity materials and the possibility of *in situ* profiling. The disadvantage is the more involved computation due to the nonlinear relationship between the TAV and the majority carrier concentration.

A verification of the TAV model and of the proposed procedure was obtained by comparing results from two separate and different experiments. TAV-V data obtained at different temperatures were also used to evaluate the temperature dependence of the free carrier concentration in the epilayer, and the impurity levels in the material.

The technique can be easily extended to different semiconductor structures and heterostructures.

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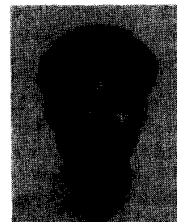
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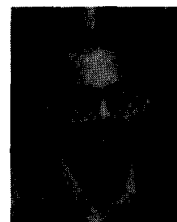
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