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Transient acoustoelectric spectroscopy measurements for the characterization of GaAs epilayer structures

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Abstract. A new measurement technique, acoustoelectric deep-level transient spectroscopy (AE-DLTS) is used to characterize the GaAs epilayer film grown on a semi-insulating GaAs substrate. The electric field, generated by the propagation of a surface acoustic wave (SAW) on a piezoelectric crystal, is used as a probing tool to study the transient behaviour of deep levels. This field interacts with the free carriers present in the semiconductor, resulting in an alteration of the carrier density at the surface of the semiconductor and the generation of a DC voltage. The rate at which excess charges are induced at the semiconductor surface, or diminished after the passage of the SAW pulse, is related to the position and the cross section of the deep levels at the interface between the epilayer and the substrate. The theoretical analysis of the fall time of the DC voltage is presented along with experimental verification. In our experiments the voltage transients were recorded as a function of incident photon energy and at different temperatures, and the thermal and optical cross sections of the EL2 level in GaAs were evaluated from computer fit.

1. Introduction

There is a growing interest in GaAs technology for high-speed integrated circuits, and in particular surface acoustic wave (SAW) devices are being fabricated on GaAs for a variety of high-speed analogue signal processing applications such as transverse filters, convolvers and correlators. 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 figure 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 performance of the device the energy of the SAW is usually contained within a thin surface layer which is commonly referred to as the transport channel. This thin layer is usually fabricated by epitaxy on a GaAs substrate rendered 'semi-insulating' during the crystal growth by deliberately inducing a relatively large concentration of EL2 defects (typically 2×10^{16} cm^{-3}) that act as deep-level donors to compensate for residual shallow acceptors [2].

The presence of deep trap levels can influence the performance of a SAW device, as it can result in signal distortion due to transfer loss. Many techniques have been developed for characterizing deep trap levels at semiconductor interfaces, e.g. capacitance–voltage [1] (C–V) and deep-level transient spectroscopy [2] (DLTS). A major drawback of these measurements is that they require the fabrication of contacts on the semiconductor. This work reports on the development of a new technique here referred to as acoustoelectric deep-level transient spectroscopy (AE-DLTS) and its utilization for characterizing the dominant deep trap level in the epilayer–substrate interface region of a SAW device.

Acoustoelectric measurements utilize the nonlinear interaction between the electric field associated with the SAW and the free carriers in the semiconductor. As a result of this interaction, the SAW is attenuated [3] and acoustoelectric currents are generated inside the semiconductor [4]. In open circuit conditions, these currents develop a voltage. The DC component of the acoustoelectric voltage, which is normal to the direction of propagation and to the surface of the piezoelectric crystal, is referred to as the transverse acoustoelectric voltage (TAV). Historically the steady-state value of the TAV signal has been used to characterize the electrical and optical

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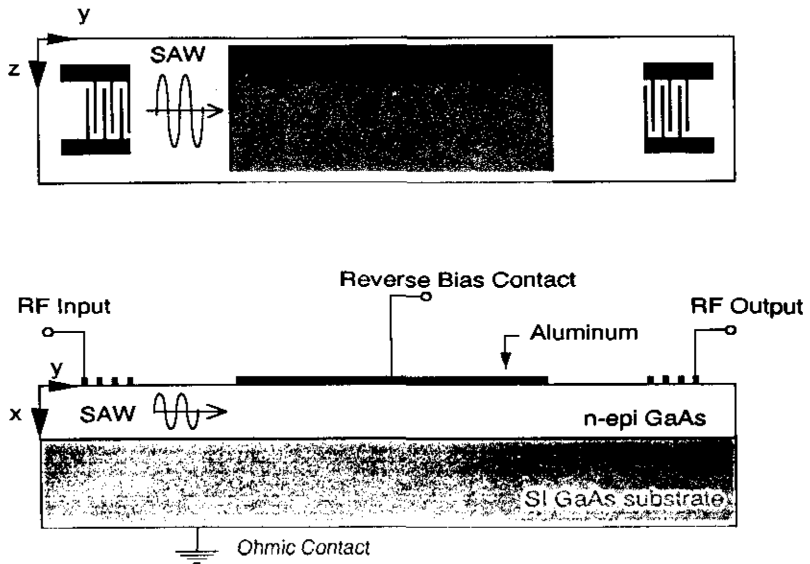

Figure 1. Semiconductor structure used for experiments. The sample has an n-type epilayer ($n = 1.3 \times 10^{14}\,cm^{-3}$) grown on SI GaAs. The SAW is generated by applying a voltage to the RF input and the TAV is detected by the large metal contact.

properties of semiconducting materials and devices [5]. The TAV transients were measured at different temperatures and as a function of photon energy. A one-level model was employed to represent the TAV fall time and used to obtain the activation energy and the thermal cross section of the dominant trap level. The optical cross section of the EL2 trap level was also obtained as a function of the incident photon energy.

The measurement here described is non-destructive in nature since it does not require the fabrication of special contacts on the semiconductor, and thus can be useful for characterizing semiconductor samples at various stages of their production cycle without increasing the level of sophistication. It has to be pointed out that the SAW is generated directly on the GaAs, which is piezoelectric, since in a SAW device the IDT is already present, as well as the Schottky contact. For a complete non-destructive and generic testing structure a different experimental set-up should be used. In this case the SAW can be generated on a piezoelectric crystal such as $LiNbO_3$, and the semiconductor is placed in contact. This is the so-called separated-medium TAV testing structure, which is described in detail in [5].

2. Experimental details

The structure used to generate the SAW and the TAV in the experiments presented in this paper is shown in figure 1. The semiconductor sample consists of a (100) n-type GaAs epitaxial layer (epilayer), 8 μm thick, grown by MOCVD on top of a semi-insulating (SI) GaAs substrate. The electron concentration in the epilayer was measured [6] to be $1.3 \times 10^{14}\,cm^{-3}$. The metal contact on top of the epilayer is used to create a Schottky diode and thus to deplete the region below of free carriers. Its dimensions are $20 \times 30\,mm^2$. The acoustic wave in the semiconductor is mainly confined to a region with a depth of about the SAW wavelength ($\simeq 40\,\mu m$ in our case), and therefore probing is mainly restricted to the epilayer and to a part of the substrate.

A block diagram of the experimental set-up used in the acoustoelectric experiments is shown in figure 2. In order to monitor the DC component of the acoustoelectric signal through possible insulators, the RF signal is modulated as a sequence of bursts; this is achieved by mixing the RF sinewave signal with a square waveform. The frequency of the SAW is 67.5 MHz and the square waveform has a typical repetition rate of 1–10 Hz with a pulse duration of the order of hundreds of μs. The output of the mixer, properly amplified, is connected at the input of an interdigital transducer on the piezoelectric crystal.

The instrumentation to monitor the acoustoelectric signal is relatively simple. Usually a high-input impedance amplifier with adjustable band-pass filter is used to detect the TAV signal. Depending on various parameters, such as the SAW power and frequency, the semiconductor resistivity and the size of the air gap between the semiconductor and the piezoelectric substrate, the amplitude of the TAV signal can be of different orders of magnitude, from microvolts to volts. The output of the amplifier is usually connected to a digital oscilloscope (Hewlett Packard 54100D) and to a lock-in amplifier (EG&G Princeton Applied Research 186A). The square waveform used to generate the RF burst is also used as a reference signal to the lock-in. The digital oscilloscope is used to digitize and save the TAV signal for rise- and fall-time measurements. All data are gathered and analysed by a computer which is connected to the instruments via an IEEE 488 (GPIB) bus and also has data acquisition and control (DAC) capabilities by means of a DAC board. A large variety of software routines were developed to acquire and analyse the acoustoelectric

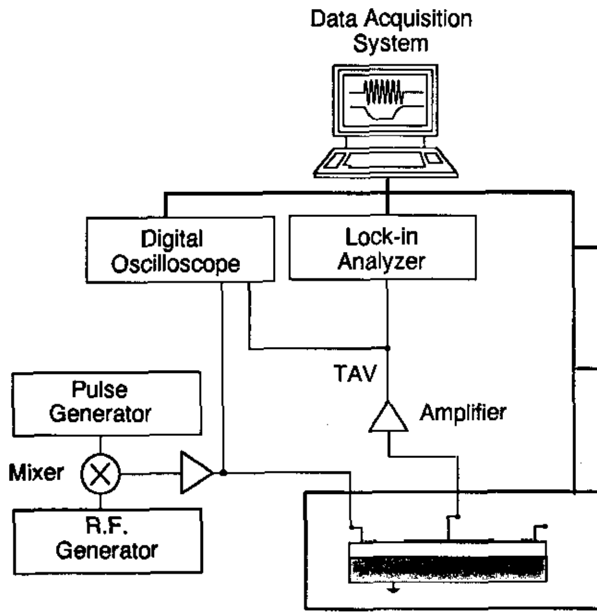

Figure 2. Experimental set-up used for AE-DLTS measurements.

voltage measurements. These programs range from data acquisition routines to theoretical numerical modelling procedures.

3. Analysis and modelling of the TAV transient

The acoustoelectric effect is based on the generation of an RF electric field due to the propagation of the SAW on a piezoelectric material [6]. The SAW is generated by applying an RF voltage to the IDT fabricated on a piezoelectric crystal, such as $LiNbO_3$, and the semiconductor is placed in close proximity to the surface (figure 1). Due to the piezoelectricity of the propagating medium, the mechanical strains induced by the SAW produce a dielectric polarization and thus an electric field. The field interacts with the free carriers, resulting in an accumulation of majority carriers at the surface, which in open circuit conditions is detected as a DC voltage (TAV). The SAW is modulated as a sequence of pulses with a repetition period of seconds. The resulting TAV signal resembles a square wave with rise and fall times sometimes in the range of milliseconds to seconds even through the time constant associated with the SAW pulse is in the nanosecond range. Typical time signals are shown in figure 3.

The importance of trapping effects in acoustoelectric phenomena has been recognized and described in various papers [1, 3, 7]. In the approximation of a single dominant trap level, the change in occupancy of the trap level Δn_{t0} due to the acoustoelectric interaction and in particular to the nonlinearity of the generation–recombination processes can be expressed as [8]

$$\Delta n_{t0} = \frac{G_{nl}}{\sigma_n v_{th} N_c} \exp(\Delta E_t/KT) \qquad (1)$$

where G_{nl} represents the nonlinear term of generation

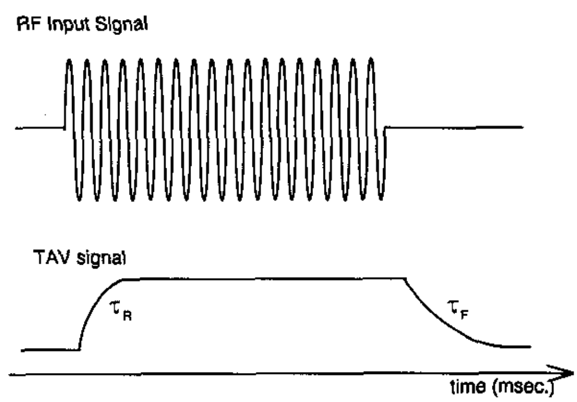

Figure 3. Time signals of the RF input used to generate the SAW (top) and of the resulting TAV signal (bottom).

and recombination at the trap level due to the SAW-induced electric field, σ_n is the thermal capture cross section, v_{th} is the average thermal velocity and N_c is the effective density of states at the edge of the conduction band E_c. K is the Boltzmann constant, and the trap activation energy ΔE_t is measured relative to E_c.

The inherent nonlinearity of the recombination–generation processes produces a net change in the trapped charge, an effect which is analogous to the nonlinear current which generates the TAV. At the end of the SAW pulse, the acoustoelectric component of the TAV decays to zero almost instantaneously (the time constant is given by the sample relaxation time), while a voltage component due to the trapped charge remains and decays to zero with a characteristic time τ_F (figure 3). This component of the TAV, due to the trapped charge, often has the same sign as the acoustoelectric part; but it has been observed that in some published experimental measurements the two components can have different sign [7].

The time dependence of the trapped charge is expressed as

$$\Delta n_t(t) = \Delta n_{t0} \exp(-t/\tau_F) \qquad (2)$$

with

$$\tau_F = (\sigma_n v_{th} N_c)^{-1} \exp(\Delta E_t/kT). \qquad (3)$$

The TAV signal measured on the oscilloscope (figure 3) can thus be expressed as

$$\mathrm{TAV}(t) = \mathrm{TAV}_0 \exp(-t/\tau_F). \qquad (4)$$

Therefore the TAV fall time (τ_F) can be used to detect and study trap levels in the semiconductor. The ionization energy and cross section of the trap level can be easily measured by monitoring the change in τ_F as a function of the sample temperature or of the energy of an incident light beam.

This analysis was obtained by assuming only one trap level, since the acoustoelectric interaction mainly affects the occupancy of the trap level close in energy to the Fermi level. However, the result can be readily generalized.

4. Characterization of the EL2 level in GaAs

The measured TAV fall time is mainly sensitive to the trap level near the Fermi level (E_F), thus if the Fermi level is varied by other means, such as temperature, bias voltage or light, the TAV transient can be used to characterize the trap levels [5]. These measurements are similar to the conventional DLTS technique [9], their usefulness lying in the characterization of high-resistivity materials, since DLTS is limited to semiconductors with free-carrier concentrations larger than the deep trap level concentrations [10]. The TAV transient was thus measured at various temperatures and an Arrhenius plot of the results is given in figure 4. The temperature dependence of the fall time τ_F can be expressed as

$$\tau_F = (\gamma_n \sigma_n T^2)^{-1} \exp(\Delta E_t/KT). \qquad (5)$$

Thus the slope of the Arrhenius plot yields the activation energy ΔE_t, while the horizontal axis intercept is utilized to obtain the thermal cross section σ_n. From the data in figure 4 the thermal cross section σ_n for the trap level was calculated to be 7.22×10^{-14} cm^2, with an activation energy of 0.736 eV. This result agrees well with values obtained by other researchers for the EL2 level [11].

A different kind of experiment, in which the sample is illuminated by a monochromatic light, is now presented. The effect of illumination is to photoionize deep levels so that they will be able to participate in the acoustoelectric effect and thus in the emission process by which they are characterized. By varying the wavelength of the light, the ionization energies for different trap levels are detected, in addition to their corresponding optical cross sections. This method is analogous to the one presented in [12], where DLTS is performed by using a small voltage pulse in conjunction with steady-state illumination.

A Bausch and Lomb monochromator was used to illuminate the sample with incident photon energy

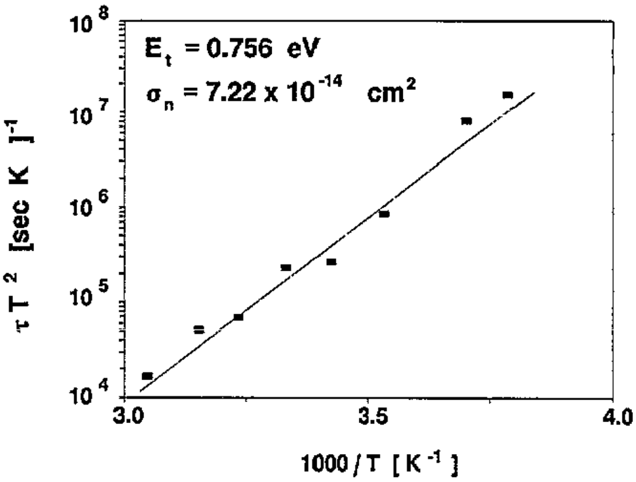

Figure 4. Arrhenius plot of (τT^2) for the TAV fall time.

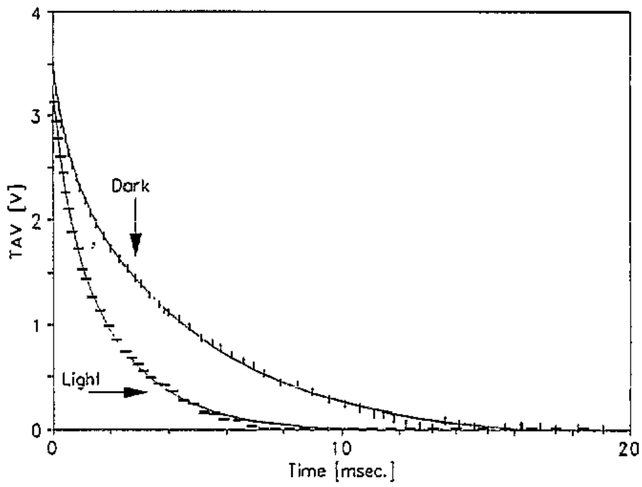

Figure 5. TAV transient measurements performed in the dark and under illumination with a 0.848 eV monochromatic light. The horizontal and vertical short dashes represent the experimental values, and the full lines represent the computer fits, calculated assuming a single exponential.

varying from 0.5 to 1.3 eV. For each measurement, the semiconductor sample was in steady-state condition before, during and after the SAW pulse. Figure 5 shows the digitized transient for the TAV in the dark and under a 0.848 eV illumination. The sharp change in the decay constant τ_F can be explained by considering the combined effects of illumination and acoustoelectric interaction in the semiconductor. The expression for the transient fall time is thus modified to include the effect of illumination:

$$\tau_{FL}^{-1} = \sigma_n v_{th} N_c \exp(\Delta E_t/KT) + \Phi\sigma^{(o)} = \tau_{FD}^{-1} + \Phi\sigma^{(o)} \qquad (6)$$

where τ_{FL} and τ_{FD} represent the measured TAV fall times under steady-state illumination and in the dark respectively; Φ is the light intensity and $\sigma^{(o)}$ is the optical cross section. By measuring both time constants (τ_{FL} and τ_{FD}), equation (6) yields the value of the optical cross section. Results are shown in figure 6 as open squares, while the two lines represent measurements presented in the literature for the EL2 room-temperature optical cross

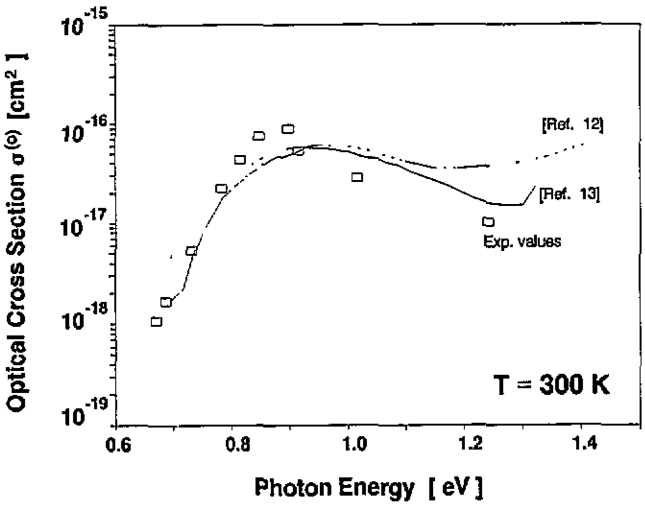

Figure 6. Calculated values for the optical cross section of the EL2 level ($\sigma^{(o)}$) as a function of the incident photon energy. Curves refer to values obtained from [12] and [13].

section [13]. There is some disagreement for the values of cross section measured for higher photon energies. At this time it is not possible to understand the reasons.

5. Conclusions

A new technique, acoustoelectric deep-level transient spectroscopy (AE-DLTS) is presented and utilized to characterize the dominant trap level at the interface region between the epilayer and the semi-insulating substrate of a GaAs device. By measuring the change of the TAV fall time as a function of temperature and incident photon energy, the thermal cross section and activation energy of the EL2 level in GaAs was measured, as well as the spectral distribution of its optical cross section.

As the proposed measurement is analogous to conventional DLTS measurements, all the improvements and discussions presented over the years on the DLTS technique are equally applicable for AE-DLTS experiments.

The measurements show the possibility of using TAV measurements on high-resistivity semiconductors, leading to its utilization for characterizing deep levels in the mid-gap range [5, 6, 8]. This is not possible using conventional DLTS, even though high-resistivity materials can be examined by optical excitation during DLTS in a technique commonly termed photoinduced transient spectroscopy (PITS).

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