NONDESTRUCTIVE TAV SPECTROSCOPY TO DETECT IMPURITY LEVELS IN SEMICONDUCTOR BY SCANNING THE ENERGY GAP WITH BIASING ELECTRIC FIELD*

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ABSTRACT

The presence and location of an impurity level at the surface of a p-type, B-doped 9-10 Ωcm Si sample is detected using transverse acoustoelectric voltage (TAV) spectroscopy in the presence of a biasing field. TAV spectroscopy has been previously used to study semiconductor surfaces and its sensitivity is increased by using an electric field to change the surface condition of the semiconductor. The biasing electric field is used to scan the forbidden gap of the semiconductor by the Fermi level. Thus, depending on their position relative to the Fermi level, the impurities can be selectively ionized. The process of detecting an impurity level by the above technique is as follows: The semiconductor is placed at the surface of a $LiNbO_3$ sample. The nonlinear interaction beteen the free carriers at the surface of the semiconductor and piezoelectric waves at the surface of the $LiNbO_3$ develops TAV across the semiconductor. The amplitude of the TAV signal is monitored to study any changes in surface conductivity. A monochromatic light is directed at the surface of the semiconductor. The photon energy is varied and the TAV spectrum is obtained. Upon shining a monochromatic light with proper photon energy, the ionized donors and neutral acceptors trap the electrons from the valence band increasing the net hole population. On the other hand, the neutral donors and ionized acceptors lose their electrons to conduction band increasing the net electron population. TAV versus the energy of the incident light is monitored to detect alteration of the surface conductivity induced by impurity-level-trapping of the carriers. The magnitude and polarity of the biasing electric field is chosen to yield the maximum variation in the TAV signal when such trappings occur. This technique is used to detect an impurity level around 1.03 eV below conduction band at the surface of the p-type Si sample. This level is not detectable without the biasing electric field. Also, the valence to conductance band transition in low resistivity GaAs is detected. These transitions are, also, not detectable without the biasing electric field.

INTRODUCTION

The nondestructive determination of the energy interface states and impurities is of great importance in rapidly advancing fields of semiconductor technology. Knowledge of the position of these states in the bandgap of the starting material, enables one to perform wafer screening and to study the effects of subsequent device processing on the surface condition. A variety of methods have previously been developed to study these interface states [1-7] including photovoltage [4], photoconductance [5] and capacitance versus voltage (C-V) [6-8] spectroscopies. In some of these techniques, either a fabrication of a test structure at the surface of the semiconductor, such as MOS capacitor [4-7], is required or the semiconductor is immersed in an electrolyte [2]. Neither of these requirements are satisfactory in an assembly line where the electrolyte might itself contaminate the semiconductor surface and the test structures consume valuable real estate.

The transverse acousto-electric voltage spectroscopy is nondestructive and it does not require a fabrication of a test structure or immersion of the semiconductor wafer in an electrolyte. This technique was previously used to characterize the surface condition of variety of semiconductors [9-13] including GaAs [11,13]. In the previous works, the application of the TAV spectroscopy was limited to relatively high resistivity semiconductors ($\rho > 0.1$ Ωcm). The use of an externally applied d.c. bias field extends the applicability of the TAV technique to low resistivity samples as well as increasing its sensitivity in detecting certain optically induced transitions. As in the other techniques, the externally applied electric field is used to change the effective surface conductivity and the population of the interface states.

The probing tool of the TAV technique is an a.c. electric field, generated at the surface of a piezoelectric material, that is coupled to the semiconductor surface without any contact. This a.c. electric field accompanies the surface acoustic wave (SAW) in piezoelectrics extending to a distance of about an acoustic wavelength (≈ 32 μm for 110 MHz SAW) outside the surface. The SAW is generated by an r.f. pulse applied to the interdigital transducers fabricated at the surface of the piezoelectric substrate, and it travels along the surface where the semiconductor is placed (Fig. 1a,b). The a.c. electric field that accompanies SAW, interacts with the free carriers of the semiconductor developing transverse and longitudinal acousto-electric voltages (TAV and LAV). In TAV spectroscopy, the variation of TAV signal is monitored versus the energy of the incident photon

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directed at the interaction region, where SAW interacts with the semiconductor [11,12].

In this work the TAV spectroscopy is performed while an externally applied d.c. electric field is used to change the surface conductivity of the semiconductor. Fig. 1a shows the delay line ($LiNbO_3$) that is used in this work. The interdigital transducer and the interaction windows are fabricated using aluminum evaporation and conventional photolithography technqiue. Under the aluminum, the a.c. electric field that accompanies SAW is shorted out. At the interaction windows, this field is regenerated and only at this region the SAW interacts with the free carriers of the semiconductor surface. The aluminum that surrounds the interaction window is grounded and an insulator ($A\ell_2O_3$) is grown anodically over the ground path to prevent any d.c. current conduction through the semiconductor. The externally applied d.c. bias is used to generate space charge region at the surface of the semiconductor as shown in fig. 1b. These space charge regions are extended to the area above the interaction windows (Fig. 1b). Thus the effective carrier concentration in the interaction regions can be modulated by the externally applied d.c. bias through the field effect. A similar delay line was used previously in the TAV versus V_{Bias}(TAV-V_{Bias}) measurements [14]. However, it should be emphasized that the present delay line differs in three aspects: a) the dimensions of the interaction regions are much smaller (100 μm << 5000 μm), b) an insulator ($A\ell_2O_3$) is grown on the surface of the ground path, and c) parabolic waveguides [15] are used to direct the SAW and increase its power density at the interaction windows (Fig. 1a).

The smaller interaction region enables one to modulate the surface potential of the semiconductor over the interaction window where it is almost impossible to do so with a large interaction window [16]. The presence of an insulator between the semiconductor and the aluminum is essential in using the field effect to accumulate or invert the surface of the semiconductor. Also, this insulator, by preventing d.c. current conduction through the semiconductor, simplifies the analysis of the data by enabling one to assume the quasi-equilibrium condition [16]. The dependence of TAV on the effective surface carrier concentration is depicted in Figs. 2 and 3 for Si and GaAs respectively [9]. It should be noticed that the change in TAV amplitude in response to photogenerated carriers, is largest when the surface is intrinsic and, in this region, the number of photogenerated carriers can constitute a large portion of the surface carriers. Fig. 4 shows the different possible positions of the interface traps in the bandgap of p and n-type semiconductors. Various possible transitions are shown by arrows in this figure (these states are assumed to be radiative). These transitions can be detected by TAV spectroscopy only if the number of photo-exited carriers trapped by the interface states (Fig. 4 transition (ii) or the number of photoionized carriers (Fig. 4 , transition (i)) constitutes a large percentage of the free surface carriers. This condition can be easily satisfied when the equilibrium carrier concentration at the surface is the smallest (the surface is intrinsic). Thus the externally applied electric field can be used to deplete the surface of the semiconductor, enabling the optically generated carriers (transitions in fig. 4) to constitute a large percentage of the free surface carriers causing large changes in TAV amplitude.

EXPERIMENTAL PROCEDURE AND RESULTS

The experimental setup is shown in Fig. 1. The thickness of the ground path aluminum is 5000 A° and to prevent any a.c. current conduction through the semiconductor, 1000 Å $A\ell_2O_3$ is anodically grown [17], over the ground path. The interaction windows are defined using photolithography and their diameters are 100 μm. The d.c. bias field is applied to the surface of the semiconductor as shown in Fig. 1b. Due to nearly ohmic nature of the back contact, the space charge region is only generated at the surface of the semiconductor where the interaction with SAW occurs. If there is any insulator at the back of the semiconductor, the space charge region will also be generated there. Thus, to obtain the value of voltage drop at the surface of the semiconductor, the amount of the voltage drop at the back of the semiconductor has to be taken into account. A Bausch and Lomb spectrometer is used to perform the TAV spectroscopy and the power of the incident beam, measured by thermopile, was 0.5 mW. The properties of the samples are summarized in Table I The Si samples are degreased and boiled in $HC\ell$ for 30 minutes and the surface of GaAs samples were cleaned and 1000 A° Layer is removed by anodic oxidation and subsequent etching of this oxide by 30°C $HC\ell$.

The experimental TAV-V_{Bias} curve for sample (a) is shown in Fig. 5. The SAW power was 20 mwatt and the SAW pulse duration was 3 msec with a repetition rate of 7 msec. The experimental TAV-V_{Bias} curve was used to calculate the density of interface traps as a function of interface trap energy (D_{it}-E_{it}) [18]. Fig. 6 shows this curve in addition to D_{it}-E_{it} curve which was obtained using high-frequency C-V technique [19]. The biasing conditions that are depicted in Fig. 4 were used in performing the TAV spectroscopy of sample (a) (Fig. 7). As shown in Fig. 7, the TAV spectrum, when the surface is weakly accumulated or inverted (points 1 and 4 in fig. 4), indicates that the surface is p-type when the photon energy is higher than the bandgap energy. The surface conductivity approaches the dark value, set by the biasing condition, when the incident photon energy is lower than the bandgap energy. However, when the surface is depleted (point 2 and 3 in fig. 4), a transition around 1.03 eV contributes to the surface conductivity changing the TAV amplitude. Since the TAV amplitude becomes more positive, it can be deduced that this transition makes the surface more n-type. Thus the presence of interface traps 1.03 eV below the conduction band can be postulated to account for the increase in TAV amplitude around 1.03 eV incident photon energy. The presence of these traps is also suggested by the shape of the D_{it}-E_{it} curve around 1.03 eV (Fig. 6). More evidence pertaining to the presence of these traps was also found by performing C-V spectroscopy, and as shown in Fig. 8, there is a structure in inversion capacitance versus incident photon energy curve around 1.03 eV. It should be noted that these structures are distinct enough to rule out the possibility that the smear-out of the valence-to-conduction-band transition (transition (iii) in Fig. 4) might be responsible for the observed data.

The results of TAV spectroscopy for low resistivity GaAs samples (b) and (c) are shown in fig. 10. The biasing field is primarily used to deplete the surface of these low resistivity samples to increase the effective resistivity and, hence, to increase the TAV amplitude. The biasing condition for sample (b) is shown in fig. 9 and the surface of sample (c) was depleted by 5 volts biasing voltage. In these experiments, the valence-to-conduction-band transitions are detected, and a higher intensity spectrometer was needed to obtain the interface trap-to-band transitions. More interesting results were found in the case of high resistivity Cr-doped GaAs samples (samples (d) and (f)). These samples are the same except that the surface of sample (f) etched with $30^{o}C$ buffered HCℓ. The TAV spectrum of sample (d) is shown in fig. 11. There was about 100-200 A^{o} native oxide on the surface of this sample and, hence, a large interface trap density could be expected. The TAV spectrum of sample (d) indicates that, when the spectrum is obtained by tracing the energy of monochromatic light from higher-than-the-band-gap energies to low energies, a prominant peak can be detected around 1.41 eV. This peak, although with smaller amplitude, also exists when the energy of the incident photon is traced in the opposite direction (low energies → high energies). Moreover, the amplitude of the TAV signal in the previous case (high → low) falls off somewhat slower than the latter case (low → high) [20]. These observed data can be explained by the presence of interface traps with large densities [21] that emit their carriers when the energy of the incident photons become lower than the bandgap energy. However, when the energy of the monochromatic illumination is traced from lower-than-the-bandgap energies to high energies, the traps are not as occupied as in the first case to contribute to TAV amplitude in the low energy part of the spectrum and the TAV amplitude falls off faster (fig. 11). Similar peaks also occur in photo-resistivity and photo-response spectroscopy of a variety of semiconductors, and, it is well known, that they can be explained by the presence of interface traps with large densities [5,4,22]. The TAV spectrum of sample (f), shown in fig. 12, indicates that the peak around 1.41 eV is not detectable and the TAV amplitude falls off much faster at the low energy part of the spectrum. These results suggest the removal of the native oxide by HCℓ reduces the interface traps' density to a degree that they are no longer detectable. A portion of fig. 11 is shown in fig. 12 to emphasize that the presence of interface traps with large density, shifts the roll-off point of TAV amplitude from E_{ph} = 1.42 eV to E_{ph} = 1.41 eV. The TAV spectroscopy under biasing was also performed on sample (d) to study the effect of the electric field on TAV spectrum and interface traps.

Fig. 13 shows that when the surface is depleted, the peak, due to interface traps, is no longer detectable. However, it should be noticed that the roll-off of the TAV amplitude still occurs at 1.41 eV indicating that by depleting the surface, the TAV amplitude in the high energy part of the spectrum might have been increased and the interface to conduction band transition still exists. This can be explained by the fact that when the surface is depleted, the high energy photons penetrate more into the sample contributing more effectively to the TAV amplitude. The shape of the TAV spectrum when the surface is accumulated (fig. 13) also supports the above explanation. As is shown in Fig. 13 the TAV amplitude is very small at the high energy part of the spectrum of the accumulated surface indicating that the majority of the high energy photons are absorbed at the surface where the recombination rate is very high.

CONCLUSION

In summary, a new technique that uses a biasing d.c. electric field, to set the surface condition, to increase the sensitivity of the TAV-spectroscopy is described. With the use of this technique, interface traps centered around 1.03 eV below the conduction band of Si, and valence-to-conduction-band transitions in low resistivity GaAs samples are detected. These are not detectable without using the biasing electric field. It is shown that the externally applied d.c. electric field can be used to change the surface condition and extend the applicability of TAV-spectroscopy to low resistivity samples.

In addition, the surface of the high resistivity Cr-doped, GaAs is studied and a band of interface traps at 1.41 eV below the conduction band is detected. It is found that density of these interface traps can be reduced substantially by etching the surface of the samples in $30^{o}C$ buffered HCℓ and it is also found that their effect on the TAV spectrum can be modified by the biasing electric field.

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TABLE I

Semiconductor	Sample	Dopant	Impurity Concentration cm^{-3}	Oxide Thickness (A°)	Surface Direction
Si	a	Boron	$N_a=2.71\times10^{14}$	3800	<100>
GaAs	b	Tellurium	$N_d=10^{16}$	1000	<100>
GaAs	c	Undoped	$N_d=10^{14}$	1000	<100>
GaAs	d	Chromium	$N_d=10^{7}$	100-200	<100>
GaAs	f	Chromium	$N_d=10^{7}$	Less than 50	<100>

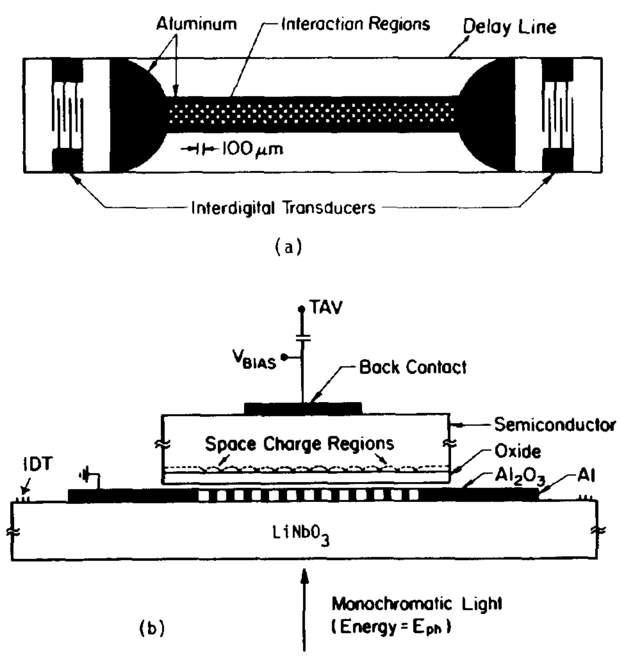

Fig. 1 The delay line and experimental setup used in TAV-Spectroscopy Technique (not drawn to scale).

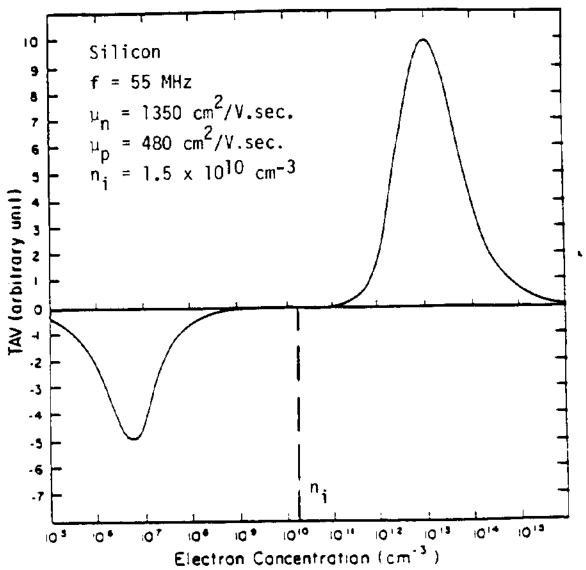

Fig. 2 TAV versus electron concentration for Si.

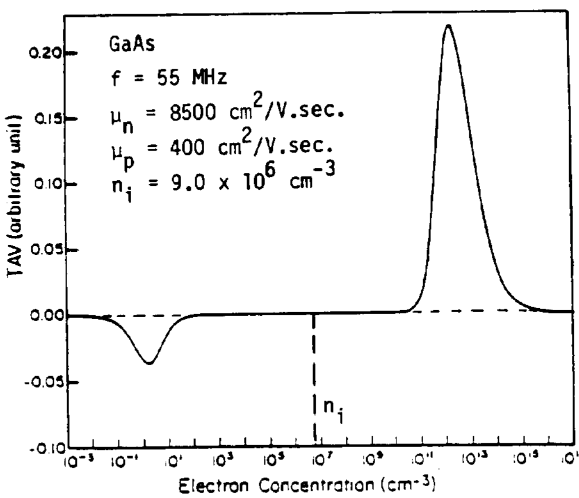

Fig. 3 TAV versus electron concentration for GaAs.

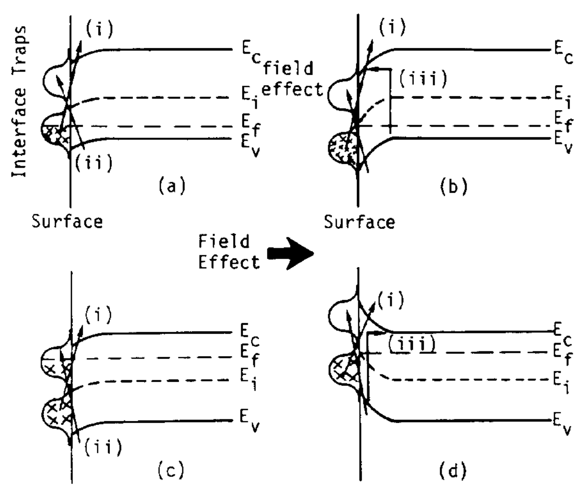

Fig. 4 Different transitions that can occur at the surface of a semiconductor

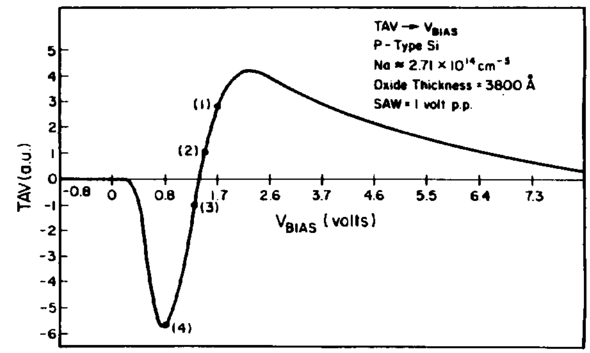

Fig. 5 TAV versus applied bias voltage for Sample (a). The biasing conditions shown in this figure are used to obtain Fig. 7.

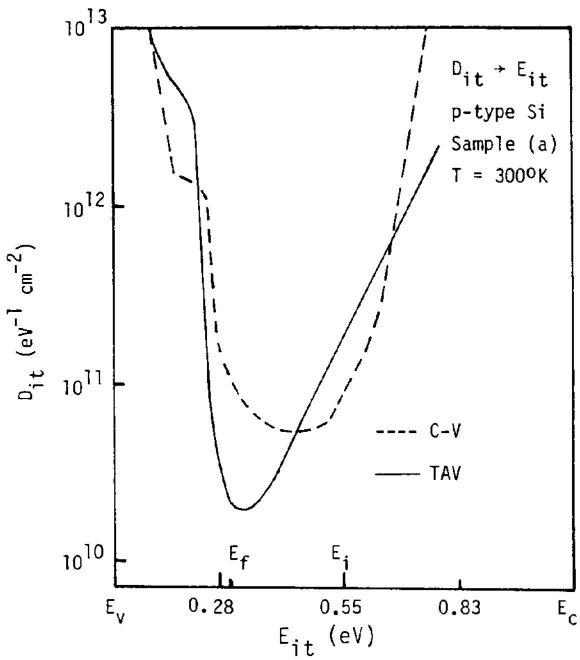

Fig. 6 The density of interface traps versus trap energy for Si Sample (a) calculated using TAV and C-V techniques.

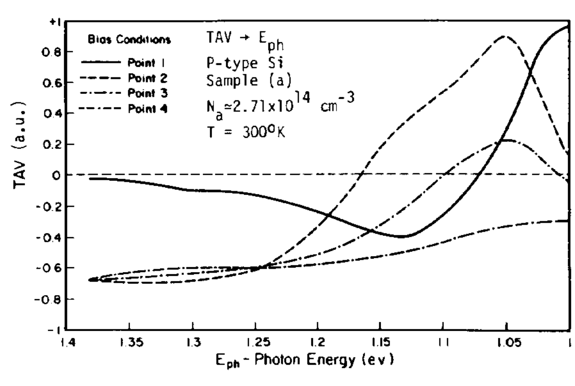

Fig. 7 TAV versus photon energy for Si Sample (a). The biasing points are shown in Fig. 5.

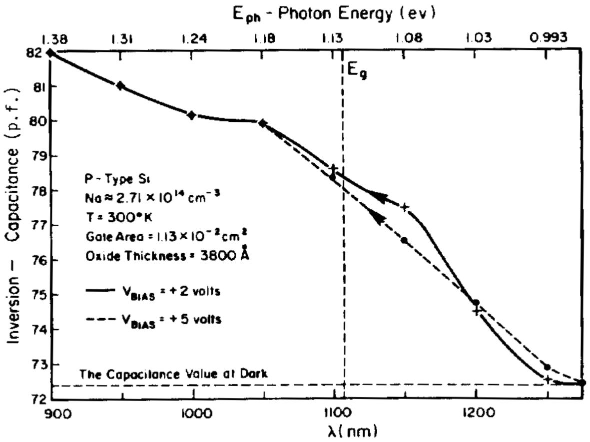

Fig. 8 Inversion capacitance versus incident photon energy for Si Sample (a).

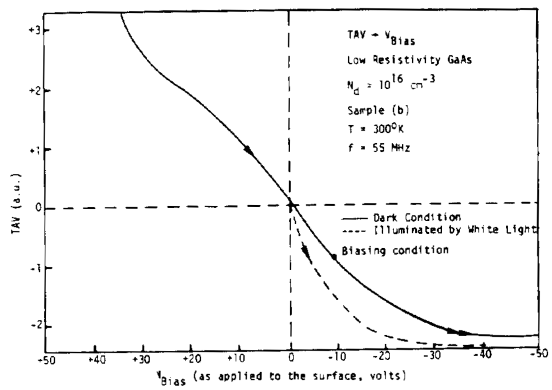

Fig. 9 The TAV versus applied bias voltage for low resistivity GaAs Sample (b).

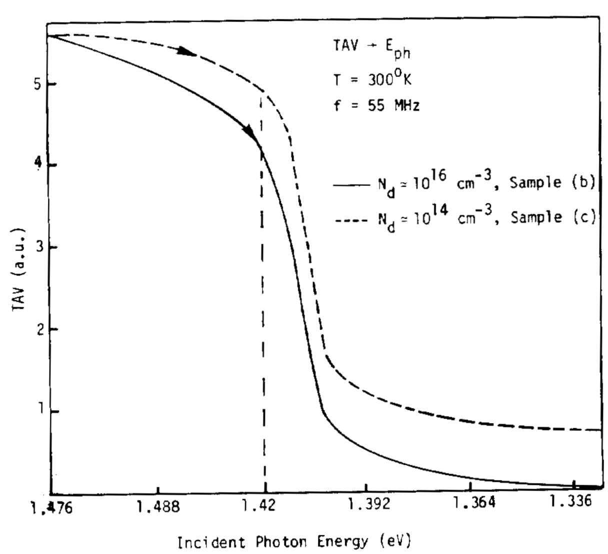

Fig. 10 TAV versus E_{ph} for low resistivity GaAs Sample (b) and (c). The biasing condition for Sample (b) is shown in Fig. 9 and the surface of Sample (c) was depleted by 5 volts.

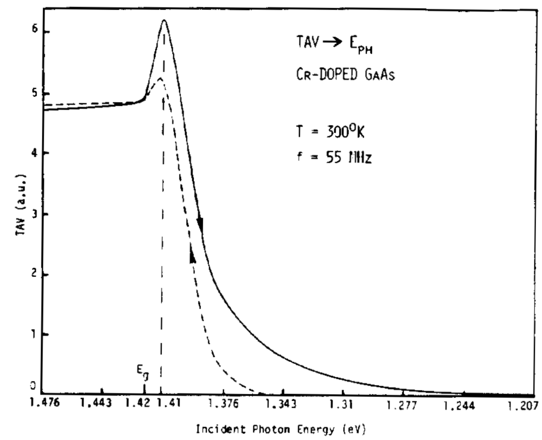

Fig. 11 TAV versus E_{ph} for Sample (d). The surface of this sample had 100-200 A° native oxide.

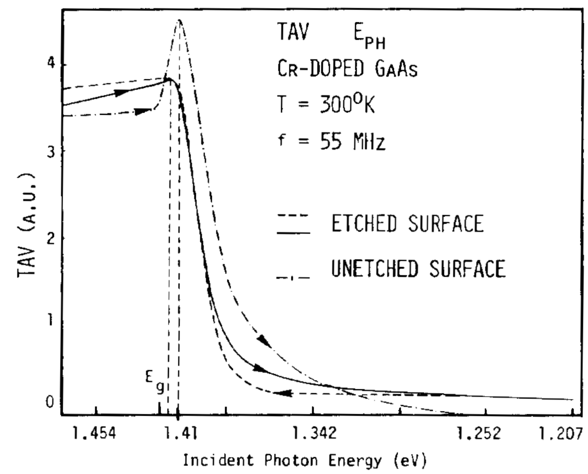

Fig. 12 TAV versus E_{ph} for Samples (d) and (f). The effect of etching by 30°C HCℓ on the TAV spectrum.

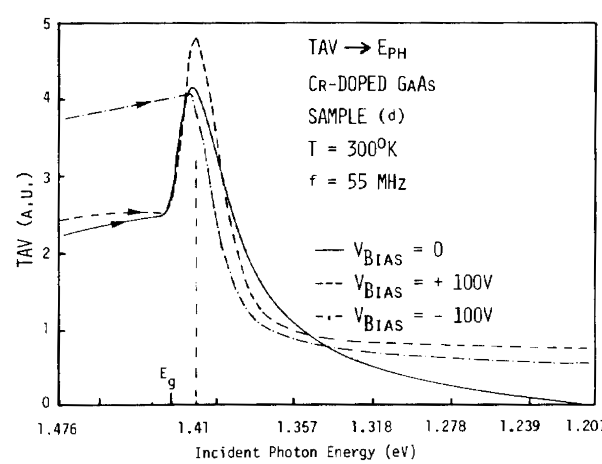

Fig. 13 TAV versus E_{ph} curve for Sample (d) under different bias condition.