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# CONTACTLESS CHARACTERIZATION OF SEMICONDUCTORS USING LASER-INDUCED SURFACE PHOTO-CHARGE VOLTAGE MEASUREMENTS

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13. ABSTRACT (Maximum 200 words)  <b>A new technique to evaluate the electrical properties of semiconductor wafers and devices using surface photo-charge voltage (SPCV) measurements is presented. SPCV measures the change in the surface electrical charge induced by a chopped laser light whose photon energy exceeds the band gap energy of the semiconductor sample. This charge is measured capacitively, thus SPCV measurements do not require the fabrication of metal contacts. In photo-charge voltage spectroscopy measurements, the SPCV is measured as a function of the energy of a sub-band gap monochromatic steady-state illumination, and its derivative spectrum is associated with the density of surface states. A qualitative analysis of the proposed measurement is presented along with experimental results performed on gallium arsenide samples passivated with a thin zinc selenide film of variable thickness. The proposed technique is completely contactless, and it can be used as an in-line nondestructive characterization of semiconductor wafers during the various stages of integrated circuits fabrication.</b>			
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## INTRODUCTION

Characterization of semiconductor materials and devices plays an important role in the area of solid state device processing. As the level of integration of electronic circuits increases, the performance of such devices is heavily affected by the presence of impurities or defects. Many techniques have been developed for characterizing defects' states at semiconductor surfaces and interfaces, i.e. capacitance-voltage (ref 1) and deep level transient spectroscopy (ref 2) (DLTS). Various optical techniques have also been used for many years to investigate semiconductors. In particular, optical-DLTS (ref 3), surface photo-voltage (ref 4), and photo-capacitance (ref 5) measurements are the most interesting. These methods are commonly based on the detection of a voltage or of the measurement of a capacitance from a p-n junction or Schottky barrier with the measured signal normally depending on three parameters: diffusion length of minority carriers, surface recombination rate, and the resistivity of the sample.

A new method to investigate the surface properties of semiconductor samples is introduced. The photo-induced surface charge is capacitatively measured as a voltage, and referred to here as the surface photo-charge voltage (SPCV), while the sample is illuminated with a steady monochromatic light of variable wavelength. This monochromatic light is used to create a variation in the steady-state population of trap levels in the space charge region. This variation does result in a change in the measured voltage, and from the derivative of the measured SPCV as a function of the energy of the monochromatic light, the energy position and the relative density of trap levels can be estimated.

This report is devoted to a description of the photo-charge effect and to an experimental demonstration of the photo-charge voltage spectroscopy technique to investigate surface states in semiconductors. In particular, results are shown for gallium arsenide samples on which zinc selenide films were grown by metal-organic chemical vapor deposition (MOCVD) process. For small thicknesses of the film, it is found that zinc selenide is a good passivating insulator for gallium arsenide.

## EXPERIMENTAL SETUP

A block diagram of the experimental setup used in the photo-charge voltage measurement is shown in Figure 1. The helium-neon laser, used to optically excite the sample, is modulated as a sequence of bursts, using either a mechanical chopper or an acousto-optic modulator, with variable pulse length and period. The typical repetition rate for the chopper is 15 Hz with light pulses of 4-ms duration, and the amplitude of the detected signal is of the order of mVolts. The light is incident on the sample placed in a metal box to shield external electrical disturbance. The design of the metal box holding the sample is very important for obtaining large signal-to-noise ratio (ref 7). The output electrical signal is obtained from a metal plate pressed against the back surface of the sample. The front contact is made by a transparent metal plate with a dielectric spacer.

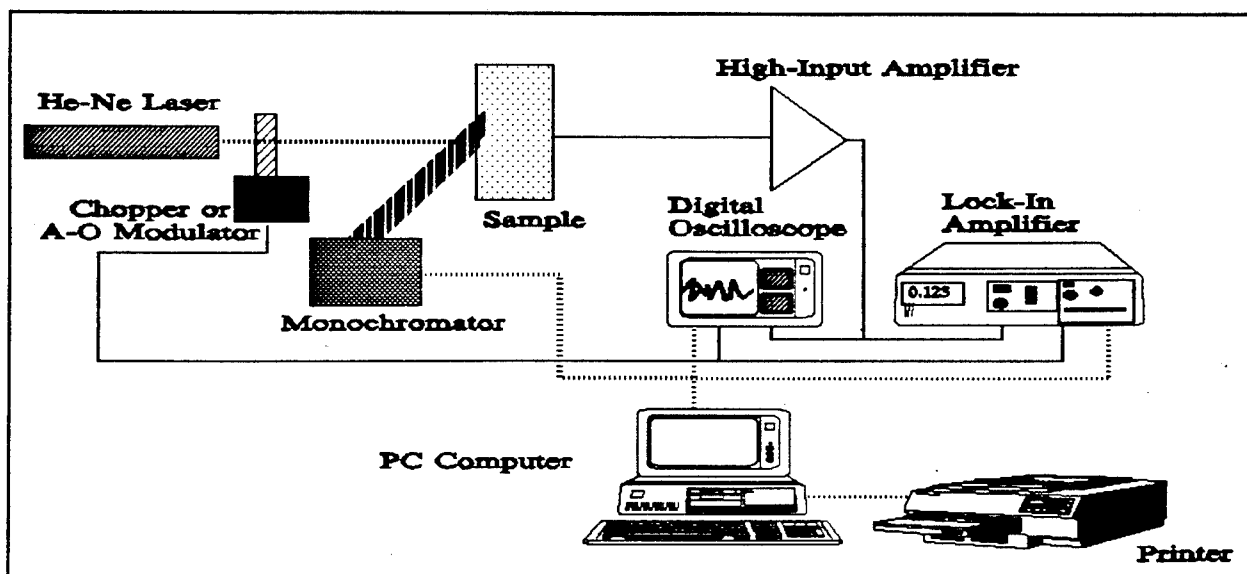


Figure 1. Experimental setup used for photo-charge voltage spectroscopy measurements.

The instrumentation to monitor the SPCV is relatively simple. The output of the sample is connected to a very high input impedance amplifier with adjustable band-pass filter. The output of the amplifier is connected to a digital oscilloscope (Hewlett Packard 54100D) and to a lock-in amplifier (EG&G Princeton Applied Research 186A). The synchronization to the oscilloscope and the lock-in amplifier is supplied by the chopper. The wavelength of the monochromatic light is varied and the relative amplitude of the SPCV is monitored with the lock-in amplifier. All of the data are memorized in the computer. The helium-neon laser has a measured output power of 7 mWatt, with a calculated photon flux  $\Phi_L$  of  $2 \times 10^{18} \text{ cm}^{-2} \text{ sec}^{-1}$ . A high-intensity Baush & Lomb monochromator, with output power of 0.18 mWatt, was used in the experiments. The calculated photon flux  $\Phi_M$  is  $5 \times 10^{14} \text{ cm}^{-2} \text{ sec}^{-1}$ , which is high enough to generate a variation in the surface charge, but still is order of magnitudes less than the laser probe.

## QUALITATIVE DESCRIPTION OF THE PHOTO-CHARGE EFFECT

Light incident on a semiconductor can cause the generation of carriers, provided the energy of incident photons is larger than a critical value (ref 6). The photo-charge effect (ref 7), described herein, is observed in semiconductors with lights of all photon energy and also in conducting materials (ref 8). In metals, the effect can be explained by considering the attenuation of an electromagnetic wave incident to a conductive surface (ref 9). For semiconductors, the photo-charge effect is also dependent on the presence of surface charges due to trap levels.

SPCV is generated by the modulated laser beam, which induces a variation in the surface charge. Since the SPCV is measured capacitatively, no net current is present across the sample, thus the photo-induced charge is constrained within the space charge region of the semiconductor sample, resulting in a redistribution of the total charge compensated by a

decrease in the potential inside the semiconductor space charge region. In steady state, the optical generation of free charge carriers is thus balanced by the recombination at the surface and by the diffusion in the bulk. The amplitude of the detected voltage is calculated as:

$$V_L = \frac{q \cdot w \cdot \Phi_L}{\left[ S_p + \frac{L_p}{\tau_p} \exp\left(\frac{q\psi_s}{KT}\right) \right]} \cdot \frac{1}{C_{sc} + q \cdot N_{ss}} \quad (1)$$

where  $q$  represents the electron charge. From Eq. (1), it is clear that  $V_L$  is function of (a) the surface space region through the surface band bending  $\psi_s$ , the width of the space charge region  $w$  and its capacitance  $C_{sc}$ ; (b) the surface states through the surface recombination velocity and the density of surface states ( $S_p$ ,  $N_{ss}$ ); and (c) the bulk trap levels through the lifetime and average depth ( $\tau_p$ ,  $L_p$ ).

The response of the semiconductor sample to the laser illumination is thus influenced by the equilibrium conditions existing in the material prior to the laser pulse. Under illumination due to a monochromatic light of energy below band gap, a voltage  $V_M$  is also measured using our setup. In this case, free carriers are generated by optical transitions assisted by trap levels, and the term  $q\Phi_L$  in Eq. (1) is replaced by the product  $q\Phi_M\sigma^oN_t$ , where  $\sigma^o$  and  $N_t$  represent the optical cross section and the density of the trap level involved in the photo-generation process, respectively.

## PHOTO-CHARGE VOLTAGE SPECTROSCOPY

In photo-charge voltage spectroscopy measurements, the sample is illuminated by a steady-state monochromatic light, and the laser is pulsed. When the sample is illuminated by a constant monochromatic light of energy  $E_M = h\nu_M$ , and with an intensity  $\Phi_M < \Phi_L$ , the conditions of the semiconductor sample, prior to the laser pulse, are varied. In this case, the measured voltage is referred to as  $V_D$ . In Figure 2 the photo-charge voltage  $V_M$  is plotted as a function of the energy  $E_M$  of the monochromator, and also for comparison the amplitude of the SPCV due to the laser ( $V_L$ ) is plotted as a straight line. If the sample is illuminated by a steady monochromatic light, the amplitude of SPCV is related to the conditions in which the semiconductor is found prior to the laser pulse. If the intensity of the monochromator is high enough to create an excess of free carriers in the space charge, but is still less than the intensity of the laser, the amplitude of the measured voltage  $V_D$  can be related to the difference between  $V_L$  and  $V_M$ . A plot of the experimental  $V_D$  as a function of  $E_M$  is also shown in Figure 3. The relationship between the three SPCV measured in different conditions is clearly perceived, and it is used in the following to evaluate the density of trap levels. To extract the density of the trap levels using photo-charge voltage spectroscopy measurements, a new quantity  $A_p$  is introduced:

$$A_p(E_M) = \frac{V_L - V_D}{V_L} = \frac{\Phi_M}{\Phi_L} \int \pm \sigma^o(E, E_M) \frac{dN_t}{dE} dE \quad (2)$$

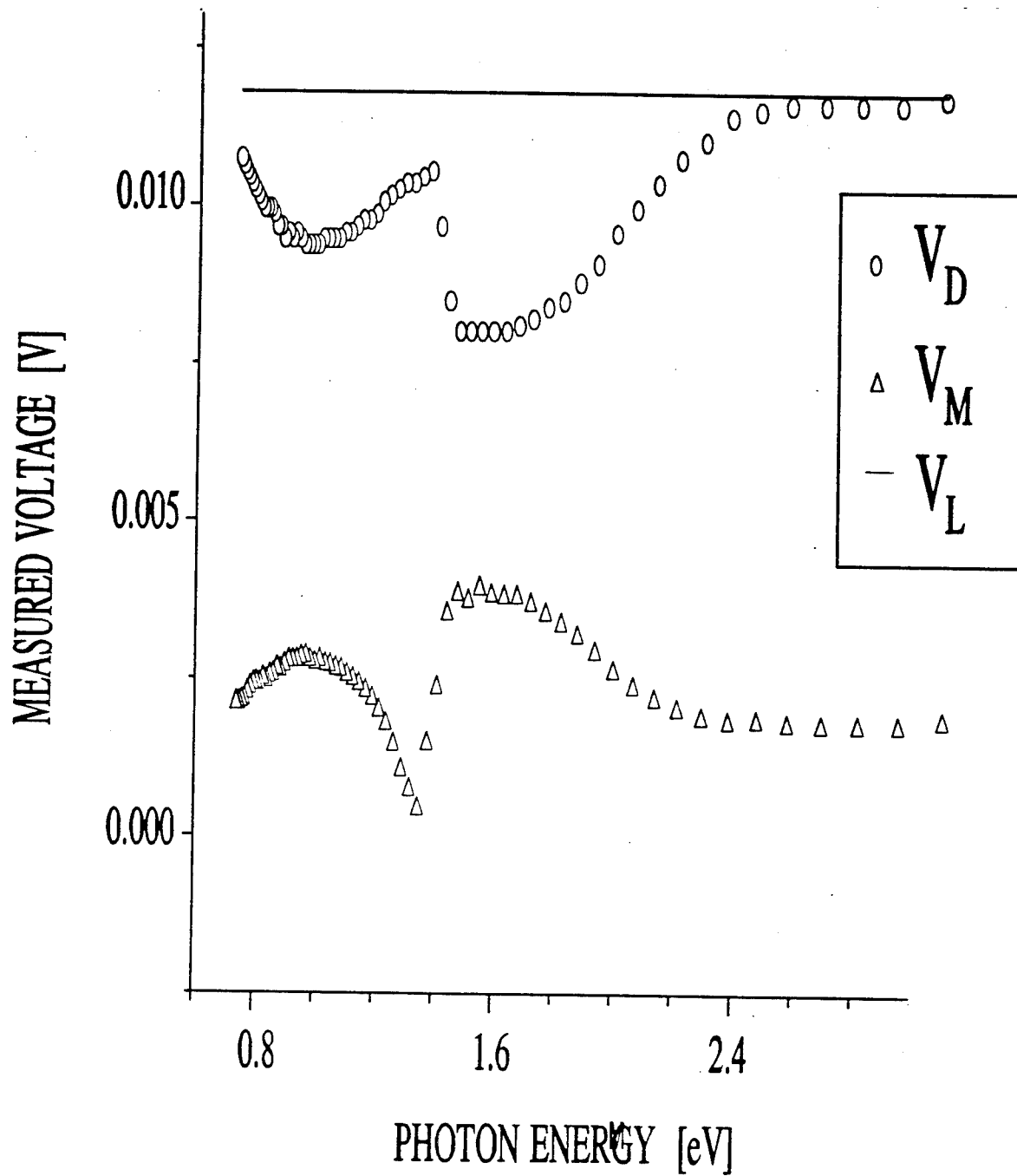


Figure 2. Plot of the experimental photo-charge voltage measured on a gallium arsenide sample. A detailed explanation is found in the text.

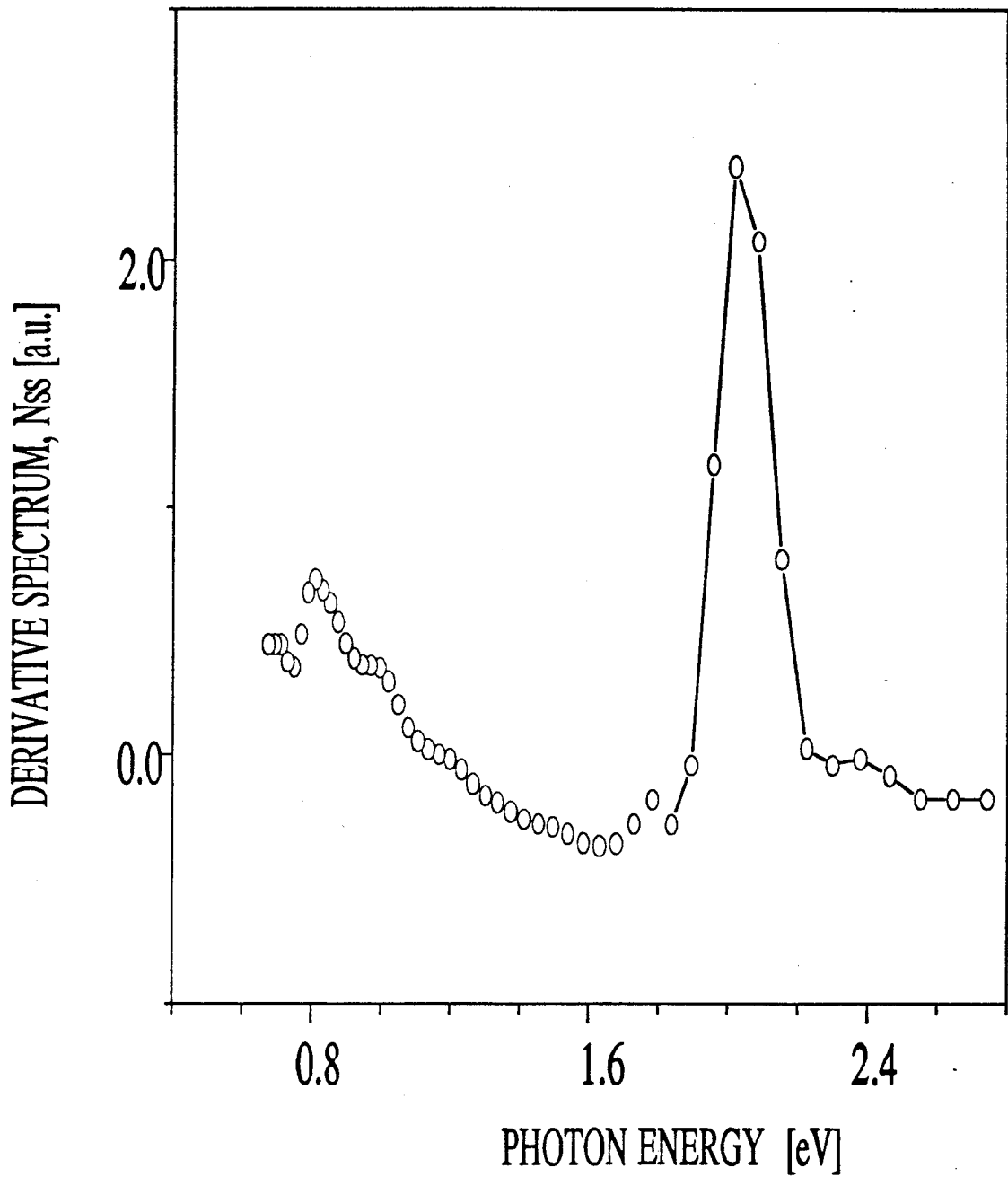


Figure 3. Plot of the relative density of the surface states  $N_{ss}$  calculated using the derivative spectrum  $A_p$ .

where the integral is extended to all energies. The  $\pm$  sign is due to the fact that a transition can either increase or decrease the total concentration of minority carriers in the space charge region. It has also to be pointed out that the quantity  $A_p$  is dimensionless, whose first derivative as a function of the energy  $E_M$  can be represented as:

$$\frac{dA_p}{dE_M} \propto \int^{\pm} \frac{dN_t}{dE} \frac{d\sigma^{\circ}(E, E_M)}{dE_M} dE. \quad (3)$$

As a first approximation, the optical cross section  $\sigma^{\circ}(E, E_M)$  can be represented by a step function with its derivative given by a delta function at  $E=E_M$ . Hence the observed derivative spectrum of  $A_p$  plotted as a function of  $E_M$  is a representation of the trap density of states. A plot of the derivative spectrum of  $A_p$  is given in Figure 3 for the  $V_D$  data of Figure 2. The transition due to the gallium arsenide band gap is easily discerned along with a distribution of states in the 0.8 eV range.

## CHARACTERIZATION OF THE ZINC SELENIDE/GALLIUM ARSENIDE INTERFACE USING PHOTO-CHARGE VOLTAGE SPECTROSCOPY

Recently there has been an increasing interest in the possibility of obtaining faster electronic devices through the use of compound semiconductors such as gallium arsenide. Unfortunately, the surface properties of gallium arsenide are relatively poor compared to silicon, with a detrimental effect on the performance of surface-oriented devices. Proper passivation of the unsatisfied bonds at the gallium arsenide surface is increasingly important as the device sizes shrink. Many attempts have been made to improve the surface quality of gallium arsenide using anodic oxides, photo-chemical treatments, and other insulating materials. However, these efforts have not yet yielded completely satisfactory results (ref 10). An alternate method of passivating the gallium arsenide surface is to grow an epilayer of a high quality semiconductor that ties up the dangling bonds at the interface.

Zinc selenide, with its large band gap, compatible thermal expansion coefficient, and lattice constant (0.25 percent mismatch) is an attractive choice for use as a passivation layer. It has been shown that thin pseudomorphic zinc selenide films, grown by epitaxy on gallium arsenide, reduce the surface recombination velocity (S.R.V.) at the interface. The effect of a zinc selenide epitaxial layer on the surface properties of gallium arsenide was studied by comparing the SPCV derivative spectra for samples of different zinc selenide epilayer thicknesses. The relative density of trap levels was thus determined as a function of the thickness of the zinc selenide film. The experimental SPCV curves are shown in Figure 4. The band gap of the zinc selenide is estimated to be 2.667 eV (refs 11,12), in that range of energies, the  $V_D$  is a linear function of the thickness of the zinc selenide film. A plot of the peak value of  $A_p$  for energies higher than 2.7 eV as a function of the thickness of the zinc selenide film is given in Figure 5. This result can be explained by replacing the quantity  $w$  with the film thickness  $d$  in Eq. (1). The maximum value of the SPCV derivative spectrum for energies below the band gap of the gallium arsenide is plotted in Figure 6 as a function of the thickness of the zinc selenide film. For comparison, the density of the interface defect density (ref 11) and the surface recombination velocity (ref 12), measured as a function of zinc selenide thickness, are also

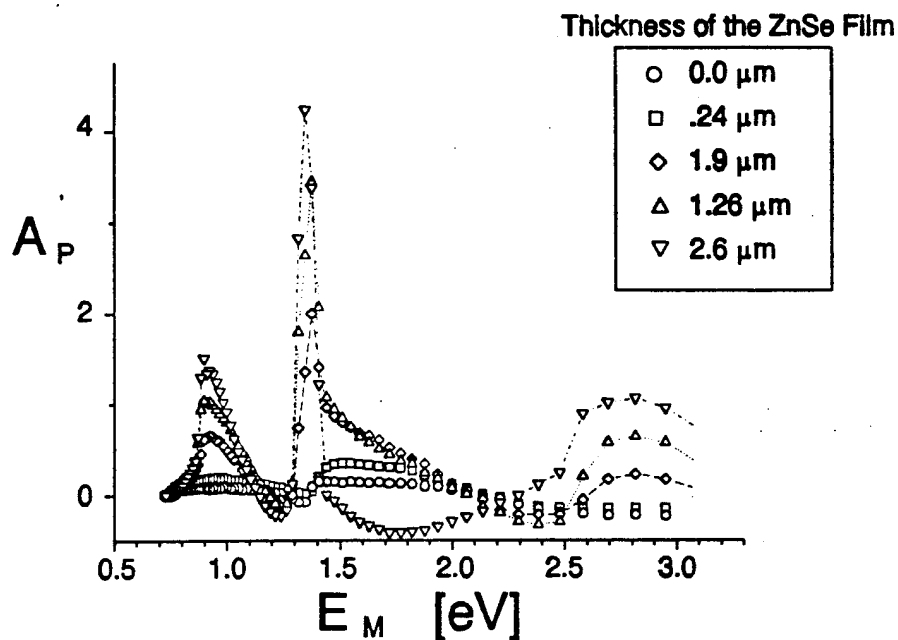


Figure 4. Experimental SPCV spectra measured for gallium arsenide samples with different zinc selenide thickness.

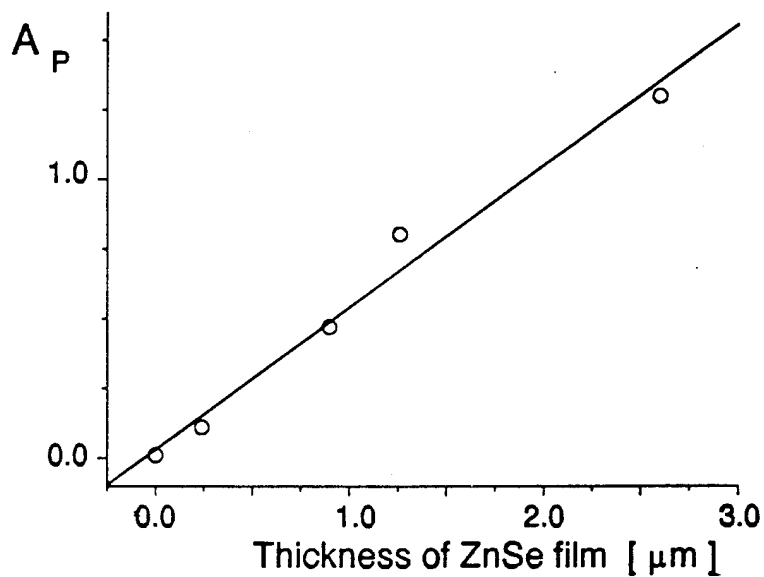


Figure 5. Amplitude of the  $A_P$  term as a function of the thickness of the zinc selenide film.

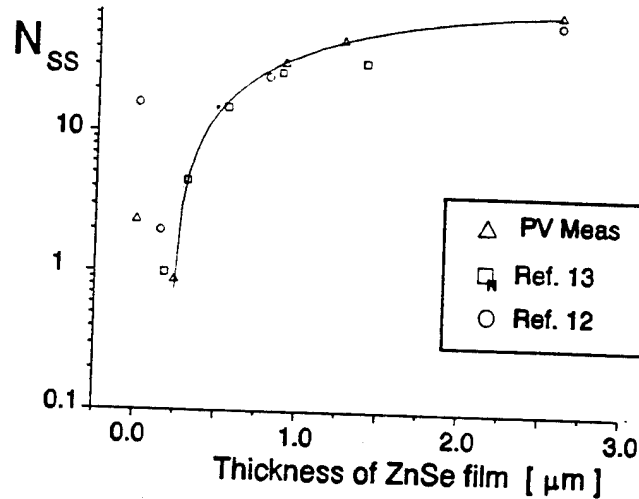


Figure 6. Plot of the relative values of the density of surface states as a function of zinc selenide thickness obtained by SPCV measurements and compared with other results.

plotted in the figure. It is interesting to note that the density of surface states, and thus the surface recombination velocity, initially decreases for the pseudomorphic zinc selenide layer and increases for thicker samples. This is an expected result, since the small lattice mismatch (0.25 percent) between zinc selenide and gallium arsenide generates a uniform elastic strain between the layer and the substrate. The amount of strain is proportional to the thickness of the zinc selenide film until a "critical thickness" is reached and the strain is relieved by the formation of defects such as misfit dislocations (ref 13).

## CONCLUSIONS

A new technique for the characterization of surface properties of semiconductor samples using surface photo-charge voltage measurements was introduced. The change in the surface electrical charge induced by illumination is capacitatively measured as a function of the wavelength of a monochromatic steady-state illumination. Gallium arsenide samples passivated with thin zinc selenide films were analyzed using the SPCV technique and an increase in the density of surface states was observed.

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