PROC. 15TH INT. CONF. PHYSICS OF SEMICONDUCTORS, KYOTO, 1980
J. PHYS. SOC. JAPAN **49** (1980) SUPPL. A p. 1125–1128

PHOTOCAPACITANCE TRANSIENT SPECTROSCOPY STUDY OF COMPOUND SEMICONDUCTOR - INSULATOR INTERFACE STATES

Hideki Hasegawa and Takayuki Sawada

Department of Electrical Engineering
Faculty of Engineering
Hokkaido University
Sapporo, 060 Japan

A new method of studying the properties of compound semiconductor - insulator interface states using photocapacitance transients is described, and is applied to GaAs, InP and GaP anodic MOS systems. The method allows direct determination of energy position and dynamic parameters of the interface states. Experimental result shows presence of high density of states near midgap in all the materials studied.

I. Introduction

The knowledge of the energy position, density and dynamic parameters of interface states is essential for the proper characterization and understanding of MOS interfaces. However, even these fundamental properties are not well established at present for compound semiconductor MOS interfaces. This is mainly because of their complicated and anomalous behavior due to high-density interface states, which makes the determination of semiconductor surface potential by the conventional C-V techniques difficult. The published state distributions and interpretations differ a great deal from author to author as pointed out in [1].

It is shown in this paper that the energy position and dynamic parameters can be directly determined by the measurement of photocapacitance transients under sub-bandgap monochromatic illumination. A simple theory of MOS photocapacitance transients is developed, and is compared with the experimental results on GaAs, InP and GaP anodic MOS systems. Good agreements between theory and experiment are obtained concerning the transient behavior. It is shown that high-density interface states of either acceptor- or donor-type appear in the vicinity of midgap in all the materials studied.

II. Theory

When interface states posses finite capture cross-sections for photons, light stimulated population and depopulation of interface states take place. In the absence of thermally stimulated transitions, the optical depopulation process can be described by

$$\frac{d\, N_s^f}{d\, t} = - \sigma_n^o\, I\, N_s^f \,, \qquad (1)$$

where N_s^f is the density of filled states, σ_n^o is the optical cross-section of interface states for electron emission and I is the incident photon flux. A similar equation in terms of the optical cross-section, σ_p^o, for hole emission and the density of empty states, N_f^e, describes the optical depopulation process. In general, optical cross-sections are complicated functions of photon energy, $h\nu$, and the energy position of the states. However, it is obvious from energy conservation that

$$\sigma_n^o = 0 \quad \text{for } h\nu < E_c - E_t \text{ and } \sigma_p^o = 0 \quad \text{for } h\nu < E_t - E_v, \tag{2}$$

where E_t is the energy position of interface states. This property enables us direct determination of E_t. As a more explicit expression of the cross-section above threshold, the follwoing formula after Lucovsky [2] for photoionization of deep impurities may be used as a first approximation,

$$\sigma^o = \text{const.} \times (\Delta E)^{\frac{1}{2}} (h\nu - \Delta E)^{\frac{3}{2}} (h\nu)^{-3}, \tag{3}$$

where ΔE is the threshold energy, $E_c - E_t$ or $E_t - E_v$.

The above optical transitions change the surface charge density of the MOS system and cause capacitance transients. Under a fixed gate bias V_G , the rate R_o of the change of the surface charge density, is related to the MOS capacitance C(t) through

$$(d/dt)(C_{ox}/C(t))^2 = \pm (2C_{ox}/q\,\varepsilon N_B)\, R_o \tag{4}$$

in the depletion approximation. Here, C_{ox} is the oxide capacitance, N_B is doping density, and ε is the semiconductor permittivity. The normalized transient waveforms calculated using eqs.(1) and (4), are shown in Fig.1. One can determine R_o by the photocapacitance transient measurements, and R_o is then related to interface state parameters through

$$\begin{aligned} R_o\Big|_{t=o} &= q\,\sigma^o I (N_{ss}\ \delta E) \\ &= \text{const.}\ q\,(\Delta E)^{\frac{1}{2}}(h\nu - \Delta E)^{\frac{3}{2}}(h\nu)^{-3} I(N_{ss}\delta E) \end{aligned} \tag{5}$$

as readily derived from eqs.(1),(3) and (4). Here, N_{ss} is the interface state density in the energy range of $E_t \sim E_t + \delta E$, involved in the transients. In the measurement, δE can be adjusted by the magnitude of the gate bias swing. For an accurate measurement, it is desirable to use a small swing of bias, and the transient in such a case will be almost exponential as seen in Fig.1. On the other hand, for a large swing, linear portion of transient extends longer.

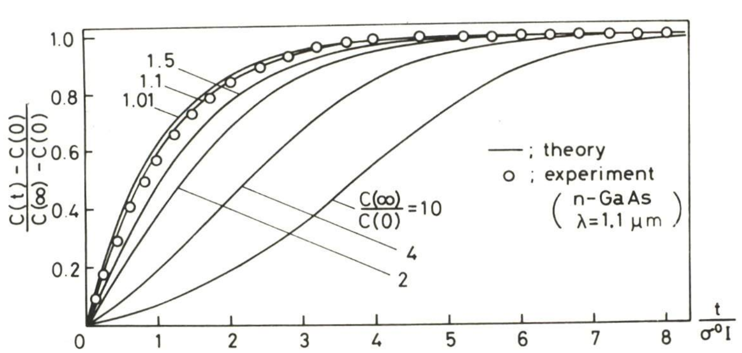

Fig.1 Calculated transient waveforms

III. Experimental Results and Discussion

Experiments were carried out on n-GaAs, n-InP and n-GaP MOS diodes having anodic oxides of 700-2000 angstrom thicknesses. Anodization was done by the AGW process[3]. Native oxides were employed for GaAs and GaP MOS diodes, whereas anodic Al_2O_3 was used for InP diodes to reduce d.c. leakage currents. Samples were annealed in hydrogen at 300 °C for 3 hours prior to measurements. Capacitance transients were measured at 100 K where no thermally stimulated transients were observed in the dark. Initially, interface states were populated with electrons up to a certain energy position by gate bias V_G. Then, the bias was reduced by a small amount, and capcitance transients at 1 MHz were measured under sub-bandgap monochromatic illumination.

Measured transient curves were in good agreements with the theoretical ones. An example, obtained on a GaAs diode, is given in Fig.1. The rate, R_o, of photo-induced surface charge variation, can be experimentally evaluated from the transient curves by noting the relation

$$R_o = C_{ox}^{-1} (dC/dt)_{light} / (dC/dV_G)_{dark} \quad . \qquad (6)$$

The measured values of R_o at a fixed wavelength are plotted vs. photon flux density, I, in Fig.2 for an InP MOS diode. An excellent linearity is seen in agreement with eq.(5).

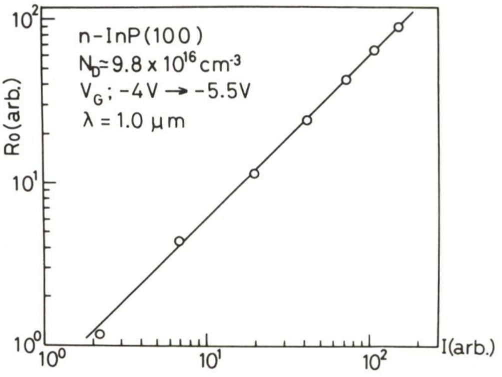

Fig.2 R_o plotted vs. photon flux density I

Measured photocapacitance transient (PCT) spectra of a GaAs diode is shown in Fig.3 for various biases. The ordinate Y is a quantity defined by

$$Y = (R_o / I)^{\frac{2}{3}} (h\nu)^2 \qquad (7)$$

According to eq.(5), Y is proportional to $N_{ss}\delta E$ $(h\nu - \Delta E)$. Experimentally, this relation was obeyed only near the threshold energy ΔE as seen in Fig.3. The fact that ΔE decreases with the increase of V_G, is consistent with the interpretation of $\Delta E = E_c - E_t$. It was found that the surface potential thus determined was in an excellent agreement with our previous data by the C-V method, providing a further support for our ISB model[1,4]. A recent comparison

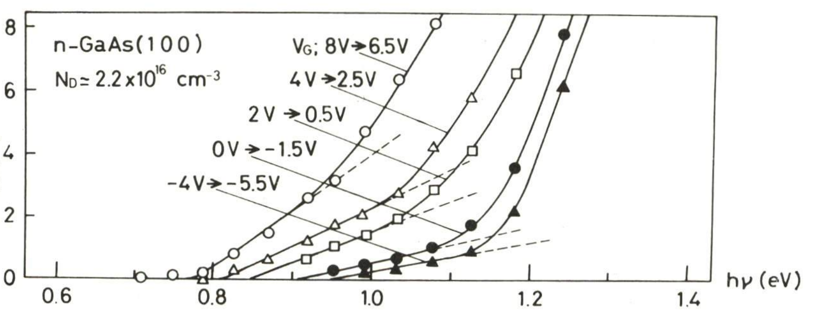

Fig.3 Observed photocapacitance transient(PCT)spectra of GaAs

between the thermal activation energy of states and the surface potential, made by Yamasaki and Sugano[5], seems to involve errors in the determination of the latter by the C-V method. PCT spectra of InP and GaP diodes are shown in Fig.4. The shape of spectrum is similar to

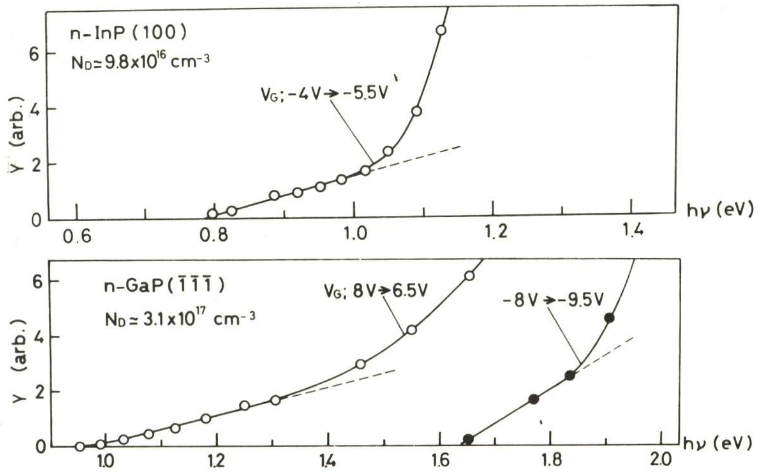

Fig.4 PCT spectra of InP and GaP

that of GaAs. Once the relationship between the gate voltage and surface potential is established, the state density distribution can be calculated by comparing it with the ideal curve. This led to the state density distributions shown in Fig.5. Sharp increase of donor and acceptor state density occurs at certain energies, E_d and E_a, in all samples as seen in Fig.5. It should be noted that either E_a or E_d is always close to the midgap. The distributions given in Fig.5 differ in various aspects from those proposed in[6].

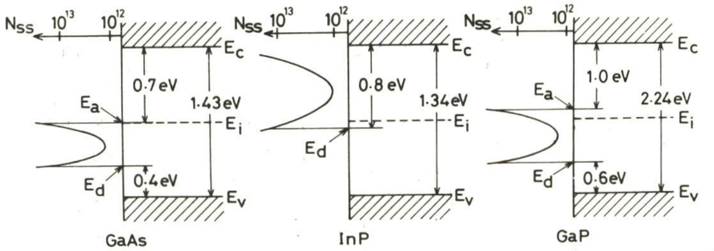

Fig.5 Interface state density distribution determined by PCT spectra(N_{ss} in $cm^{-2} eV^{-1}$)

IV. Conclusion

A photocapacitance transient spectroscopy can be used for direct determination of the energy position and dynamic parameters of interface states. Further works is required for the understanding the whole spectra, and origin of the interface states.

References

1) H. Hasegawa and T.Sawada: IEEE Trans.Electron Devices,ED-27(1980)982.
2) G. Lukovsky : Solid State Commun.3(1965)299.
3) H. Hasegawa and H.L. Hartnagel : J. Electrochem. Soc.123(1976)713.
4) H. Hasegawa and T.Sawada: J.Vac.Sci.Technol.16(1979)1478.
5) K. Yamasaki and T. Sugano: Appl.Phys.Lett.35(1979)932.
6) W.E. Spicer, P.W. Chye, P.R. Skeath, C.Y. Su and I. Lindau : J.Vac.Sci.Technol.16(1979)1422.