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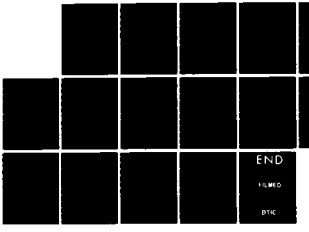

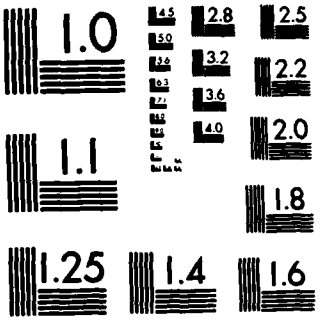

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Final Report

April 1st, 1983 to May 30th, 1984

Surface and Interfacial Properties of $Ga_{0.47}In_{0.53}As$ Alloys

Contract: N00019-83-C-0133

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Abstract

Semiconducting $Ga_{0.47}In_{0.53}As$ layers whose lattice constants match that of semi-insulating InP are, potentially, useful for discrete and integrated circuit microwave transistors and opto-electronic sensors compatible with the low loss, low dispersion spectral window of optical fibers. Their implementation requires evaluation, modelling and interpretation of the surface and interfacial properties of this ternary semiconducting compound in terms of fundamental physical parameters. We have investigated by means of field effect-controlled galvanomagnetic measurements the properties of the dielectric-semiconductor interface of (100)-oriented n-type $Ga_{0.47}In_{0.53}As$, compared these to theoretical calculations made for its "free", non-polar surface and to experimental measurements made by others on metal-insulator-semiconductor capacitors. Our results suggest that the equilibrium position of the surface Fermi level is not a strong function of crystallographic orientation and it is in good agreement with theoretical expectations, that the surface charge is slightly accumulated (<0.1 eV from flatband) at room temperature and the surface potential can be displaced over most of the fundamental bandgap across flatband into accumulation and that, just as for silicon, the electron mobility decreases with increasing accumulation surface charge in accordance with preliminary theoretical arguments.

Introduction

Semiconducting $Ga_{0.47}In_{0.53}As$ layers whose lattice constants match that of semi-insulating InP are, potentially, useful for discrete and integrated circuit microwave transistors and opto-electronic sensors compatible with the low loss, low dispersion spectral window of optical fibers. Their implementation requires evaluation, modelling and interpretation of the surface and interfacial properties of this ternary semiconducting compound in terms of fundamental physical parameters. We have investigated by means of field effect-controlled galvanomagnetic measurements the properties of the dielectric-semiconductor interface of (100)-oriented n-type $Ga_{0.47}In_{0.53}As$, compared these to theoretical calculations made for its "free", non-polar surface [1] and to experimental measurements made by others on metal-insulator-semiconductor capacitors. Our results suggest[2] that the equilibrium position of the surface Fermi level is not a strong function of crystallographic orientation and it is in good agreement with theoretical expectations, that the surface charge is slightly accumulated (<0.1 eV from flatband) at room temperature and the surface potential can be displaced over most of the fundamental bandgap across flatband into accumulation. Work performed at UCSD during the past year has been concerned principally with an evaluation of the surface properties of $Ga_{0.47}In_{0.53}As$ in accumulation. The work performed the previous year on the same n-type material has been concerned principally with the quasi-static surface properties in depletion. It has now been published[3] and it presents confirmatory evidence that the density of the surface and interface states of this ternary alloy are smaller by one order of magnitude near midgap compared to those of GaAs and are smaller by about two orders of magnitude (near the conduction band edge) compared to InP.

The $Ga_{0.47}In_{0.53}As$ Surface

Experimental investigations concerning the equilibrium position of the Fermi level at the surfaces of III-V compounds are obtained by cleaving bulk single crystals along the easy cleavage, non-polar <110> direction in ultra-high vacuum. Provided that few surface defects are introduced by the cleavage process then the bulk Fermi level coincides with the surface Fermi level, i.e., the conduction band and valence band are flat from the bulk up to and including the surface plane; the surface potential is zero. If oxygen is allowed to enter the high vacuum chamber then the chemical interaction between the oxygen and the III-V compound (110) surface produces a surface defect-induced change in the surface Fermi level. The conduction and valence bands at the surface exhibit a curvature which may be either convex or concave relative to their position in the bulk. Thus a surface potential is produced whose sign might be either positive or negative. Oxidation produces band bending at the surface; in consequence of the chemisorption and oxidation process the surface may be depleted or accumulated relative to the bulk. The type and the density of the energy states which determine surface depletion or accumulation as well as their position within the fundamental bandgap of these semiconductors is of considerable importance for improving available understanding of III-V semiconductor surfaces, to connect experimental observations to available theortical models or to modify such models in order to make them conform with new experimental measurements. Such information also bears directly on the applications of these materials for descrete devices and integrated circuits intended for microwave electronic and electro-optic components.

The investigations of "clean" (110) surfaces at flat band and the depletion of the surface charge followiong oxidation were made primarily by

means of X-ray photoemission spectrocopic (XPS) measurements on GaAs and InP. Bulk crystals are required for cleaning, therefore, only bulk grown crystals are considered suitable for such measurements. Good correlations have been obtained (for GaAS and InP, at least) between measured Schottky barrier heights and position of the surface Fermi level of oxidized (110) and (100) surfaces. In our previous annual report we have pointed out that there is, as well, a good correlation between the surface Fermi level, at equilibrium, of dielectric-semiconductor interfaces, Schottky barrier heights and, when available, XPS measurements on GaAs and InP. There is also good correlation between Schottky barrier height measurements and dielectric-semiconductor equilibrium surface Fermi level measurements made on the Ternary alloy system $Ga_xIn_{1-x}As$ where x is the fractional molar content of the respective species and x may vary from 0 to 1. No XPS measurements on cleaved $Ga_{0.47}In_{0.53}As$ are feasible because no bulk material can be grown on this ternary compound and epitaxial layers of sufficient thickness have not been made thus far. Work performed at the Naval Research Laboratory demonstrated clearly that thermodynamic and metallurgical impediments are in the way of producing bulk single crystal $Ga_{0.47}In_{0.53}As$. Thus another method had to be found to investigate the characteristic surface properties of this material.

In our earlier report to NAVAIR we pointed out that if the defect model of Fermi level priming is applicable[4] and specific, discrete, donor and acceptor states are associated with these oxidation-induced defecits then, as calculated by Allen and Dow[1] the surface donor level E_{ds} and the surface acceptor level E_{as} are both located at approximately 0.55 eV relative to the valence band edge of $Ga_{0.47}In_{0.53}As$ and the equilibrium Fermi level E_F^* as well as the Schottky barrier heights of the n-type material are, within the error of measurement, the same. Both depend on the bulk Fermi level E_F as well as

on the density of the ionized donors and acceptors which are a function of temperature as well as of the total concentration of each species N_{ds} and N_{as}, respectively.

The position of the bulk Fermi level was determined on both n-type and p-type $Ga_{0.47}In_{0.53}As$ layers grown epitaxially on semi-insulating InP substrates by means of Hall effect measurements. Therafter, these layers were made part of metal-insulator-semiconductor (MIS) two-terminal structures by depositing upon them by means of a low temperature plasma-assisted Al_2O_3 layer and an aluminum layer was vacuum deposited over it as a "gate." From capacitance vs. voltage (C-V) measurements it is then feasible to estimate the equilibrium surface potential; furthermore, the total density of the surface donors N_{ds} and surface acceptors N_{as} can be calculated[5]. These calculations lead to $N_{ds} = 5.7 \times 10^{12}/cm^2$ and $N_{ds} = 2 \times 10^{11}/cm^2$. The low density of the surface donors and surface acceptors of this ternary alloy is of particular significance when compared to the much higher densities of the interface states determined to be present on the surfaces of oxidized GaAs and InP.

Several conclusions and inferences can be drawn from all of these measurements and relevant calculations:

1. The location of E_{ds} and E_{as} at 0.55 eV relative to the valence band maximum places these defect related states in the vicinity of the conduction band minimum because the fundamental bandgap of $Ga_{0.47}In_{0.53}As$ is Eq. = 0.75 eV.
2. The metal-n-type $Ga_{0.47}In_{0.53}As$ barrier height $\phi_{Bn} = 0.2$ eV is low enough so that tunneling at the top of the interfacial barrier is possible, in p-type $Ga_{0.47}In_{0.53}As$ we can expect that the barrier height $\phi_{Bp} = 0.5$ eV is in agreement with experimental observations[6] because $\overset{\ddagger}{\phi}_{Bp} = Eg - \phi_{Bn}$

3. Acceptor densities of the order of $10^{12}/cm^2$ are required to "pin" the Fermi level in n-type $Ga_{0.47}In_{0.53}As$; however, since the calculated N_{as} is smaller than $10^{12}/cm^2$ it is feasible to displace the surface potential by means of a gate voltage applied to an MIS structure from its equilibrium value over essentially the entire bandgap without Fermi level pinning.

4. Given the position of E_{ds} and E_{as} relative to the conduction band minimum, displacement of the surface potential towards the valence band edge is not impeded by Fermi level pinning; this provides some of the necessary conditions for the construction and operation of depletion-mode and inversion-mode MISFET[7].

5. The low density of surface states below E_{ds} and E_{as} as well as near the band edges makes surface accumulation feasible in n-type $Ga_{0.47}In_{0.53}As$ MIS structures; depletion mode MISFET can be driven by means of a positive applied gate voltage from surface depletion into accumulation. This is not necessarily an advantage for some devices. Small fluctuations in surface potential produced by variations in the dielectric or ambient enviornment can change the nature of the surface from depletion to accumulation. This may affect the sensitivity and resolution of p-i-n diodes and phototransistors used in optical electronics and optical fiber sensors.

The investigations undertaken at UCSD described in this report were made on n-type $Ga_{0.47}In_{0.53}As$ in order to determine the nature of surface change accumulation produced in MIS structures using Al_2O_3 dielectric layers.

Specimen Preparation

$G_{0.47}In_{0.53}As$ layers grown epitaxially by liquid phase techniques onto semi-insulating InP were obtained from Bell AT&T Laboratories and from NOSC. These were fabricated into a symmetrical cross-shape configuration such as that shown in Fig. 1. The symmetrical cross is a variant of the clover-leaf specimen contour used for van der Pauw type resistivity and Hall effect measurements[8]. The advantage of such structures is that the electrode contact dimensions do not introduce appreciable measurement errors. Haeusler and Lippmann[9] have shown that magnetoresistance introduces in cross-shaped specimens an error less than 0.3% in Hall effect measurements. De Mey[10] and Versnel[11] made extended theoretical analyses of the electric field distribution in terms of equipotentials and current stream-lines of the symmetrical cross using conformal mapping representations. If the symmetrical cross is to be used in an MIS type structure (which produces changes in the charge density across its thickness produced by an applied gate voltage) then the applicability of the equations developed by van der Pauw[8] need to be examined in this context. Pauwels[12] analysed theoretically the effect of such transverse inhomogeneities and found that to first order the perturbation introduced in the Va der Pauw equations by small scale inhomogeneities can be ignored.

The structure shown in Fig. 1 consists of a rectangular cross made out of 0.25, 0.28 and 0.31 μm - thick epitaxial n-type $Ga_{0.47}In_{0.53}As$ layers by means of photolithographic techniques. An insulating Al_2O_3 dielectric layer ~ 0.12 μm in thickness with a resistivity estimated to be in excess of 10^{15}ohm-cm was deposited upon it and a window, shown by the dashed lines in the figure was opened in the oxide. Contact to the cross was made by means of these windows by vacuum depositing 20 w/o Sn-Au alloy followed by a 325°C

alloying cycle. Aluminum electrodes were vacuum deposited in order to make contact to these electrodes, as shown in Fig. 1, and a symmetrical cross-shaped gate was deposited again by evaporation of Al, registration and photolithographic processing onto the Al_2O_3 dielectric. The structure thus consists of the four contact pad terminals normally used for resistivity and Hall effect measurements and of the insulated gate to which a potential can be applied in such a manner as to alter the surface charge under the gate, i.e., a negative potential applied to the gate can cause surface depletion and a positive gate voltage can cause surface charge accumulation of the $Ga_{0.47}In_{0.53}As$ surface at its dielectric interface provided that the density of the interface states is small enough so as not to impede the transition from depletion through flatband into accumulation.

In our earlier report and the subsequently published paper[3] it was shown that for a qualitatively similar specimen configuration it is feasible to estimate the depletion depth produced by a negative gate voltage applied to it while making electrical and galvanomagnetic measurements. The resistivity and electron density obtained from such quasi-static measurements can be used to estimate the effective depletion depth under the gate and comparing it to the theoretically expected values the effective density of the interface states can be calculated. It was shown that the surface is slightly accumulated at equilibrium; for a gate voltage, $V_g = 0$ the surface potential $\Psi_S = 0.25$ eV. In the quasi-static regime all surface (or interface) states respond to an applied gate voltage. The potential barrier which appears near the estimated Schottky barrier of ~ 0.2 eV relative to the conduction band edge represents these interface states. However, mild annealing is often sufficient to remove this potential barrier[3] thus the Fermi level is not "pinned" as it is in GaAs and InP. We have undertaken to

repeat these measurements on our new specimen configuration as well as to extend them to include the transition through flatband into accumulation.

Experimental Measurements and Their Interpretation

Figure 2 shows the resistivity measured as a function of positive and negative values of the gate voltage on a 0.27 μm thick $Ga_{0.47}In_{0.53}As$ epilayer without taking into account surface depletion or accumulation, i.e., the conventional van der Pauw equations used are

$$\rho = \left(\frac{\pi d}{\ln 2}\right) \cdot \left(\frac{R_{AB,CD} + R_{BC,DA}}{2}\right) \cdot f\left(\frac{R_{AB,CD}}{R_{BC,DA}}\right) \qquad (1)$$

where $R_{AB,CD}$ denotes the clockwise identification of the contacts from a datum point and $R_{BC,DA}$ indicates the commutation of the current injection contacts and those used to measure the potential drop across the specimen developed by the constant applied current. The function f has been calculated numerically and is presented[8] in graphical form by van der Pauw. Note that $d = 0.27$ μm is the effective geometrical thickness of the specimen. Assuming the resistivity of the specimen to be homogenous and uniform and therefore independent of position and that a negative gate voltage produces a depletion depth δ then the electrical thickness of the conducting channel is

$$d = d_0 - \delta \qquad (2)$$

Assuming the depletion approximation to be applicable, then

$$\delta = \left(\frac{2E_s}{qN_D}\right)^{1/2} \cdot \left(|\Psi_s| - \frac{kT}{q}\right)^{1/2}$$

where ϵ_s is the dielectric constant of the semiconductor, N_D is its s donor density, Ψ_s is the surface potential, k is the Boltzmann's cons is the absolute temperature and q is the charge on the electron. If assumed that in Eq. (1) the apparent resistivity, $\rho_{app} = Kd_0$ but that actual resistivity $\rho_{act} = K(d_0 - \delta)$ then $Kd_0 = \rho_{act} + K\delta_0$ and, theref

$$\rho_{app} = \rho_{act} + K\delta$$

It follows that the apparent resistivity will increase as the depleti increases from its normal value at flatband, ρ_{act}. Intuitively we mi expect that the apparent resistivity will decrease as an accumulatior density is developed on the surface of the $Ga_{0.47}In_{0.53}As$ layer at it dielectric interface. The situation is illustrated in more straightf manner by the experimental data shown in Fig. 3 which shows the deper the Hall coefficient R_h measured as a function of gate voltage.

In view of the fact that this is an n-type layer involving charg transport of electrons in one conduction band the Hall coefficient is inversely proportional to the charge carrier density and therefore th measured, (apparent) Hall coefficient is

$$(R_h)_{app} = \frac{(R_h)_{act}}{1 - (\delta/d_0)}$$

The apparent Hall coefficient will increase from its value at flatbai increasing depletion depth δ produced by a negative gate voltage up

maximum depletion depth δ_{max} which corresponds to the onset of surface charge inversion where it tends towards saturation as shown in Fig. 3 and discussed in detail in our earlier publication[3]. It may be expected intuitively that an increase in the free electron density at the surface produced surface accumulation will correspondingly reduce the apparent Hall coefficient in Fig. 3 below its value at flatband. It is to be noted, furthermore, from Figs. 2 and 3 that the position of flatband appears at approximately the inflection points of the curves $\rho(V_g)$ and $R_h(V_g)$. Further data is shown in Figs. 4 and 5 which represent $\rho(V_g)$ and $R_h(V_g)$ in the accumulation region of a 0.25 μm-thick $Ga_{0.47}In_{0.53}As$ specimen whose bulk electron density was determined to be $n_b = 5.84 \times 10^{16}/cm^3$ and mobility $n_b = 6.56 \times 10^3 cm^2.V\text{-}s$ before the nominally 0.12 μm thick Al_2O_3 layer was deposited upon it. These data were selected for presentation here because they represent a smaller scatter of the experimental measurements than those shown in Figs. 2 and 3. The two sets of $\rho(V_g)$ and $R_h(V_g)$ are in good qualitative agreement.

The Accumulation Regime

An analysis of the experimentally measured $\rho(V_g)$ and $R_h(V_g)$ is more complicated than that of the corresponding values measured in the depletion regime. The complication arises primarily from the fact while the depletion layer substracts, effectively, from the total thickness d of the conducting channel through which current flows between the appropriate electrodes and thus, as stated earlier, the electrical thickness of this channel is different from that of the physical thickness, in accumulation charge transport in the surface accumulation layer is effectively in parallel with transport in the rest of the epilayer which might be considered to have bulk-like properties.

The analysis of the data can be made in terms of a two-layer model such

as discussed by Petritz[13] and Nedoluha and Koch[14] and adapted specifically to accumulation layers present on InAs by Wieder[15] and by Sites and Wieder[16].

Consider a two-layer structure such as shown in Fig. 6 which has common electrodes for both layers. The upper layer is defined as a surface layer with parameters characterized by the subscript s and the lower one by bulk-like properties characterized by the subscript b. Thus n_s and μ_s refer, respectively, to the surface electron density and mobility while n_b and μ_b refer, respectively, to the bulk electron density and mobility. For a transverse magnetic induction B applied to such a two-layer structure provided that the effective Hall angle is small, i.e., the product $\mu B \ll 1$ the effective measured conductivity σ_m and measured Hall coefficient R_{hm} are related to the corresponding parameters of each layer by[15,16]:

$$\sigma_m = (1/d)(\sigma_b d_b + \sigma_s d_s)$$

$$R_{hm} = \frac{R_{hb}\sigma_b^2 d_b + R_{hs}\sigma_s^2 d_s}{d(\sigma_b d_b + \sigma_d d_s)^2} \qquad (6)$$

In our case the thickness of the accumulation layer is of the order of a Debye length or less; therefore $d \approx d_b$. Hence,

$$\sigma_s d_s \approx d(\sigma_m - \sigma_b)$$

$$R_{hs} \approx \frac{ds}{d}\left(\frac{R_{hm}\sigma_m^2 - R_{hb}\sigma_b^2}{(\sigma_m - \sigma_b)^2}\right) \qquad (7)$$

The mobility of the electrons in the surface layer, μ_s is

$$\mu_s = R_{hs}\sigma_s = R_{hm}\left(\frac{\sigma_m}{\sigma_m - \sigma_b}\right)^2 - R_{hb}\left(\frac{\sigma_b}{\sigma_m - \sigma_b}\right)^2 \tag{8}$$

and because the surface Hall coefficient, R_{hs}, is inversely proportional to the surface charge density per unit volume, $R_{hs} = (1/qn_s)$, it follows that the sheet Hall coefficient of the surface layer

$$\frac{R_{hs}}{d_s} = \frac{1}{q\Delta n_s} \tag{9}$$

where Δn_s is the free carrier concentration per unit area in the surface layer. Equations (6) through (9) can thus be used to calculate the charge transport parameters in accumulation from data such as presented in Figs. 2 to 5. Evidently Δn_s is, as expected, a function of V_g increasing with increasing V_g. However, what we need in order to determine the nature of the surface potential dependence on V_g, $\Psi_s(V_g)$, is to first calculate the evolution of the surface potential dependence on Δn_s. This can be done from the evaluation of the fundamental relationship which connects Δn_s to Ψ_s given by Many et al[17].

$$Q_s = q\Delta n_s = (2\varepsilon_s kT)^{1/2}\left\{N_d \ln\left[\frac{2 + \exp\left(\frac{E_c - E_f - E_D - q\Psi_s}{kT}\right)}{2 + \exp\left(\frac{E_c - E_f - E_d}{kT}\right)}\right]\right.$$

$$\left. + N_c\left[F_{3/2}\left(\frac{E_F - E_c - q\Psi s}{kT}\right) - F_{3/2}\left(\frac{E_f - E_c}{kT}\right)\right]\right\}^{1/2} \tag{10}$$

where E_F is the Fermi level in the bulk produced by electrons with density N_d

from the donor level with energy E_d and E_c is the conduction band edge while N_c is the density of states in the conduction band. The $F_{3/2}$ parameters are integrals of the form

$$F_{3/2} = \frac{1}{\Gamma(5/2)} \cdot \int_0^{\infty} \frac{\varepsilon^{3/2} d\varepsilon}{1 + \exp(\varepsilon - \eta)}, \quad \varepsilon = \frac{E-E_c}{kT} \qquad \eta = \frac{E_f - E_c}{kT} \qquad (11)$$

tabulated by McDougall and Stoner and available in the monograph of Blakemore[18].

In view of the experimentally measured data of R_{hm} vs. V_g and of $\rho = (1\sigma_m)$ as a function of V_g it is a relatively simple matter to calculate the dependence of Δn_s on V_g using Eq's (7) and (9). Thereafter, assuming that $E_D \lesssim 10$ mV which is reasonable, in view of the fact that shallow donors in other III-V compounds are of the order of or less than 10 mV and that $E_c = 0$ and with the density of states[3], $N_c = 2.09 \times 10^{17}/cm^3$ in the conduction band and with the donors ionized, $N_d = n_b$ the surface potential $\Psi_s(\Delta n_s)$ can be calculated by means of Eq. (10) using numerical methods to perform the appropriate integrations. The calculated dependence of Δn_s on Ψ_s derived from the experimental data is presented in Fig. 7. It shows that a relatively small change in surface potential can produce relatively large changes in the accumulation surface charge density. The corresponding dependence of the surface potential on gate voltage is shown in Fig. 8 which illustrates that an applied gate voltage can effectively modulate the surface potential and therefore the free electron concentration of an accumulation layer on the surface of n-type $Ga_{0.47}In_{0.53}As$. Therefore accumulation made transistors used in the enhancement mode MISFET configuration are clearly

feasible. In that case it is of interest to examine the electron mobility in the accumulation layer using Eq. (8), its dependence on the applied gate voltage and therefore on Δn_s. Figure 9 shows the dependence of u_s on Δn_s determined in this manner.

The decrease in μ_s with Δn_s shown in Fig. 9 is reasonable. Similar results have been obtained[19] in silicon MOS structures and are attributed to the increase in the transverse electric field which, in accordance with Gauss' law is proportional to $q\Delta n_s/\varepsilon_s$. The decrease in n_s is probably due to an increase in scattering at the dielectric-semiconductor interface. It is worth noting that nevertheless the electron mobility is high and the transverse electric field in the accumulation layer is considerably smaller than in an inversion layer. In effect, the electron mobility in depletion mode MISFET is considerably larger than that of inversion mode transistors. We may expect, therefore, that accumulation mode transistors would also exhibit a higher electron mobility and consequently larger gain bandwidth products and higher limiting frequencies which they can function effectively as amplifiers than inversion mode MISFET.

Conclusions

The projected applications of $Ga_{0.47}In_{0.53}As$ keep on expanding. They now include filed effect transistors with insulated gates, junction gates and, at least potentially, modulation-doped transistors similar to those based on two-dimensional electron gas phenomena in GaAs-based heterstructures made by molecular beam epitaxial techniques. In addition to the electro-optic detector applications for 1.3 to 5.3 μm (in wavelength) planar photoconductive detectors based on the compensated semi-insulating material described in our invention disclosure were developed at the Lincoln Laboratory and

described[20] at the Device Research Conference (June 1984, Santa Barbara, CA). Quantum efficiencies of the order of 40% in the 1 to 1.6 spectral range and speeds of 50 to 90 Γ were obtained with these devices. All of these require a thorough understanding of the surface and interfacial properties of this ternary alloy with metals, dielectrics and with other semiconductors.

The specific measurements described in this report concern field-controlled electrical and galvanomagnetic investigations made on MIS structures which illustrate the fundamental properties of the surfaces of $Ga_{0.47}In_{0.53}As$ in the accumulation regime. The gate voltage dependence of the surface charge density and surface potential as well as that of the electron mobility in accumulation were determined and they indicate that it is relatively easy to induce surface accumulation in this ternary alloy by using Al_2O_3 as a dielectric coating. It is of some importance to determine the effects of the ambient environment as well as that of other insulators on surface accumulation. This is likely to be of particular importance for the surface posivation of photo-sensor p-i-n junctions and phototransistors whose performance depends on the supression of the dark current which is at least partly a function of surface accumulation. A paper which deals with the general aspect of III-V compound semiconductor-dielectric interfaces presented at the Annual Symposium of the American Vacuum Society in November 1983 is included here as an appendix.

Patents and Publications:

During the past year two patent disclosures applied for in collaboration with Technical Staff members of the Naval Ocean Systems Center were authorized for filing by the Office of Naval Research with the Patent Office:

1. Navy Case No. 67515, "Accumulation-Mode $In_{0.53}Ga_{0.47}As$ Field Effect Transistor," D. P. Mullin, A. R. Clawson and H. H. Wieder (authorized 10/13/83).

2. Navy Case No. 67329, "Method for Preparation of Semi-Insulating $In_{0.53}Ga_{0.47}As$ Epitaxial Layers" D. I. Elder, A. R. Clawson and H. H. Wieder (authorized 10/13/83).

The following papers were published relevant to this contact:

a) Device Physics and Technology of III-V Compounds, H. H. Wieder, J. Vac. Sci. Technol. A2, 97(1984).

b) Semi-Insulating $In_{0.53}Ga_{0.47}As$ by Fe Doping, A. R. Clawson, D. P. Mullin and D. I. Elder (Naval Ocean Systems Center), and H. H. Wieder (Univ. Calif. San Diego), J. Cryst. Growth 64, 90(1983).

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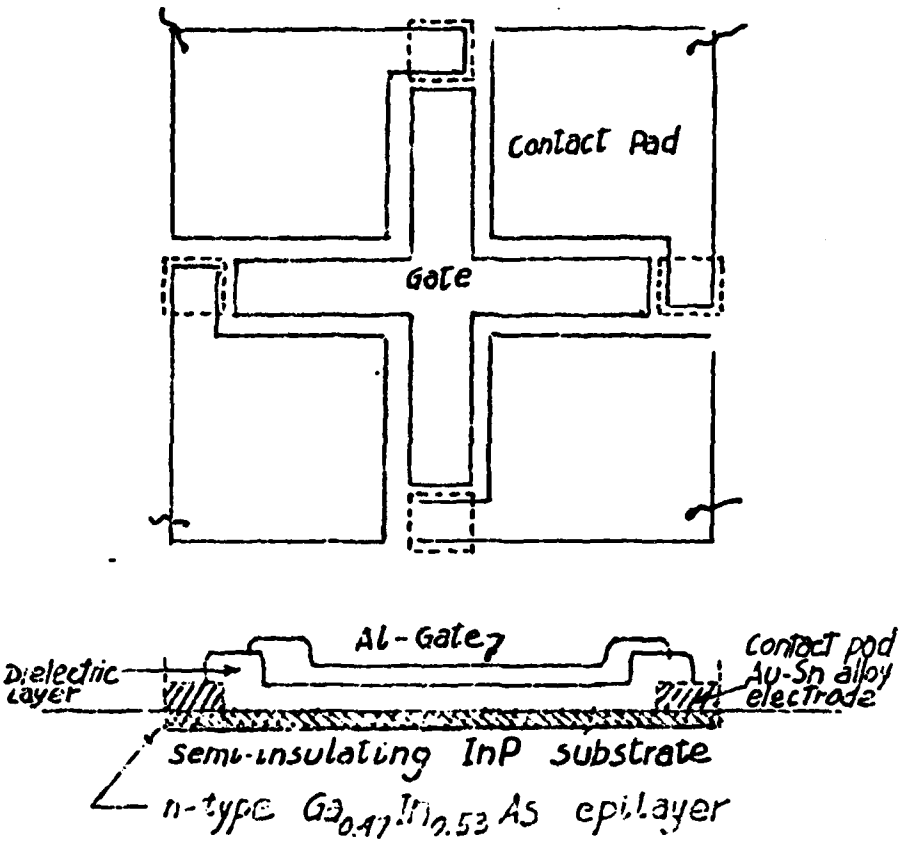


Fig. 1 Symmetrical Cross configuration used to investigate gate voltage-dependent resistivity and Hall coefficient.

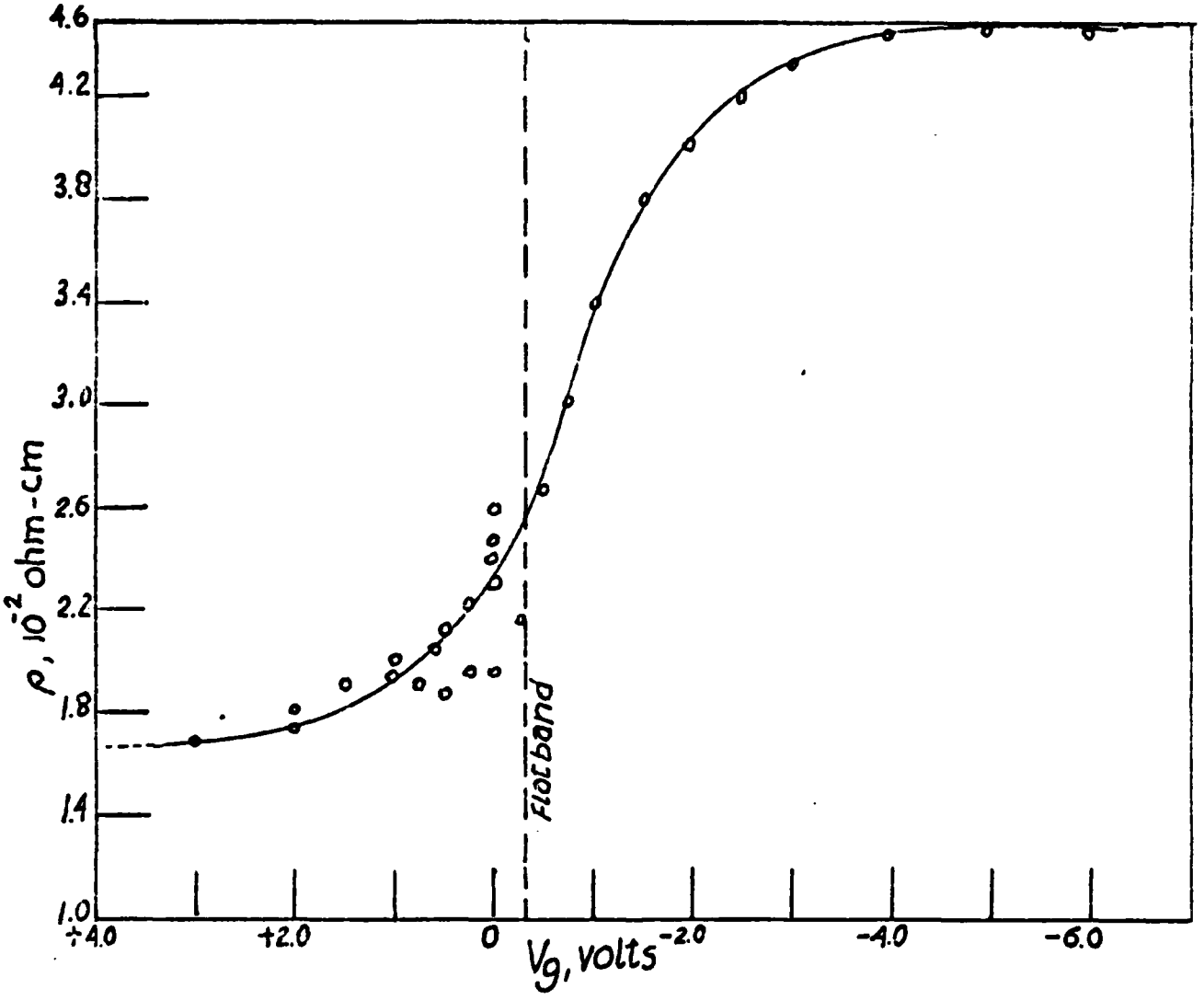


Fig. 2 Resistivity of a structure such as shown in fig. 1 in the depletion and accumulation regime calculated by means of eq. (1) as a function of applied gate voltage.

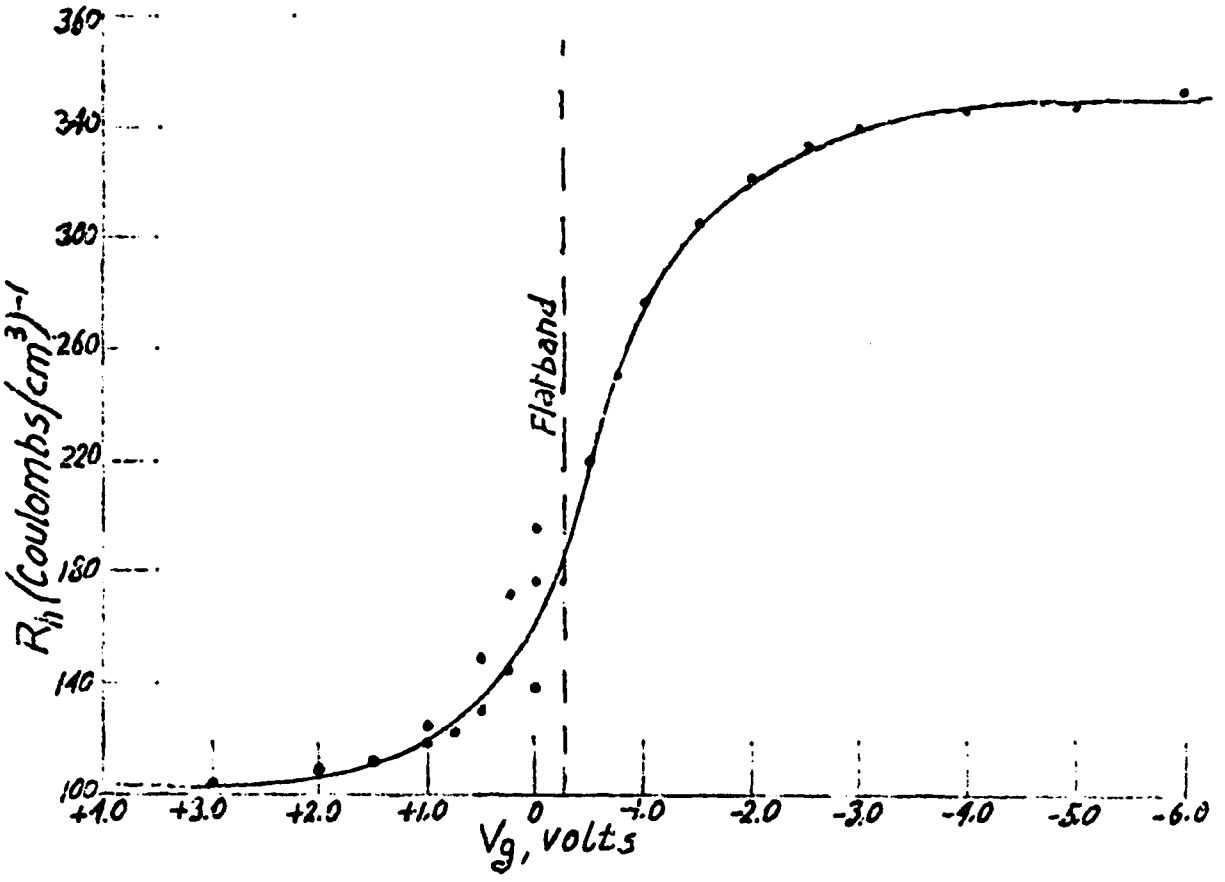


Fig. 3 Gate voltage dependence of the Hall coefficient in the depletion and accumulation regimes of the same specimen whose resistivity is shown in Fig. 2

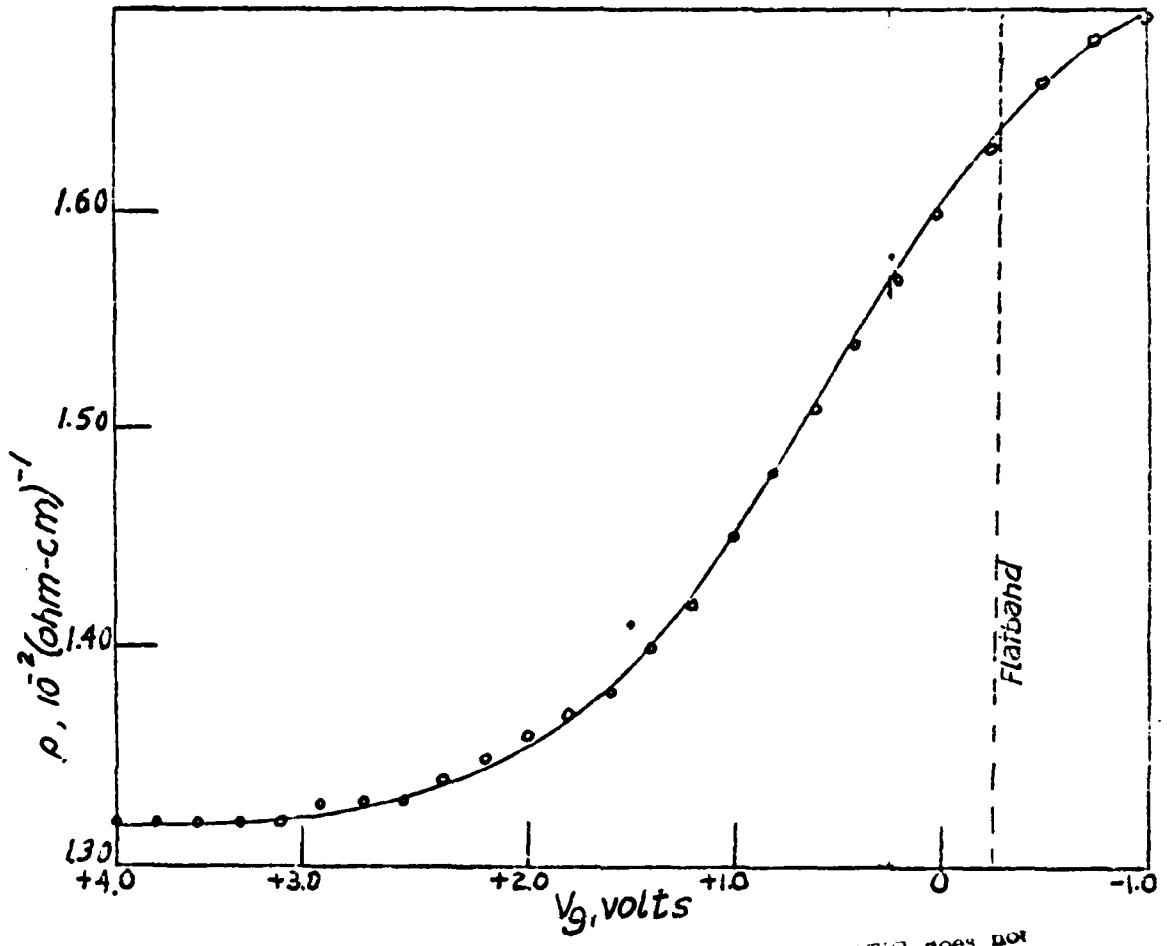


Fig. 4 Resistivity as a function of gate voltage of a 0.25 μm thick $Ga_{0.47}In_{0.53}$ MIS structure whose electrical parameters are given in Fig. 5 in the accumulation regime.

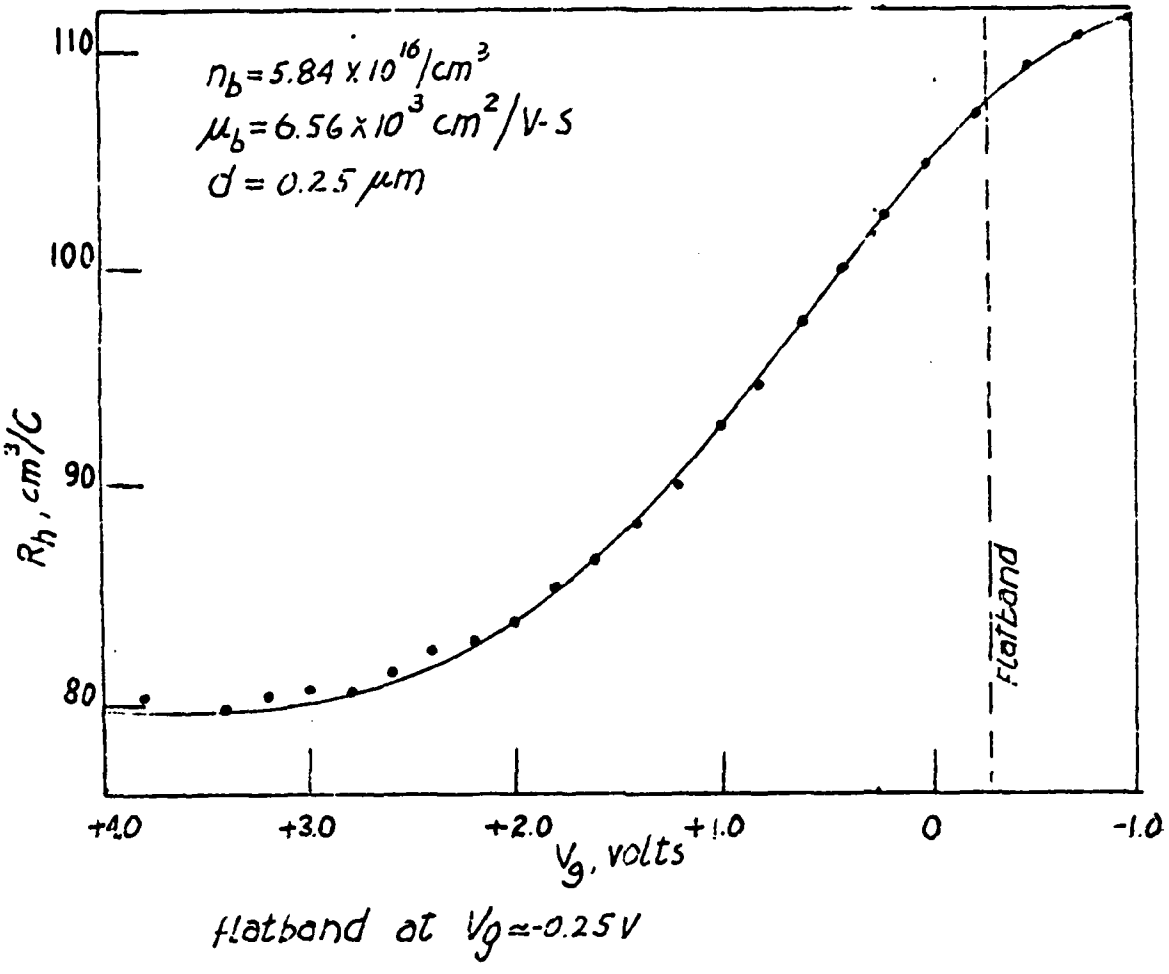


Fig. 5 Hall coefficient as a function of gate voltage in the accumulation regime of same specimen shown in Fig. 4.

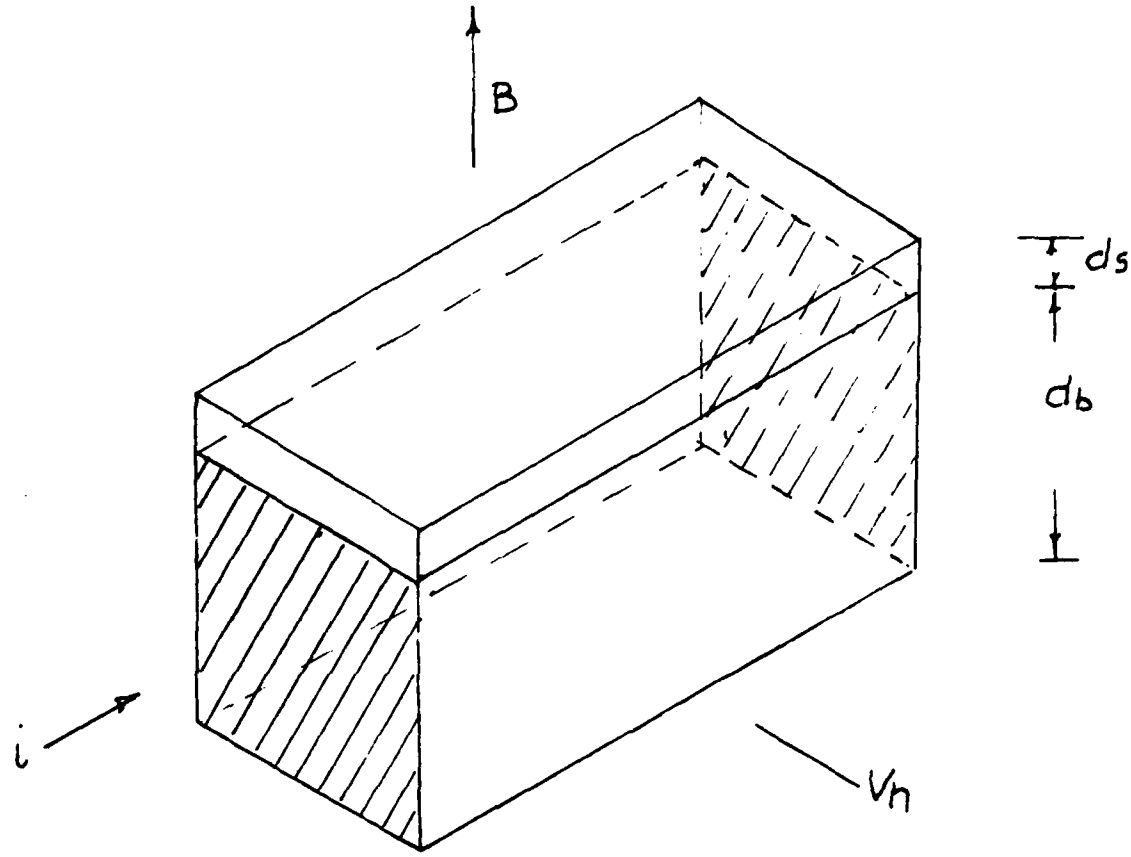


Fig. 6 Representation of a two layer model for surface accumulation on a bulk-like semiconductor. Magnetic induction B is transverse to the current i and perpendicular to the layer.

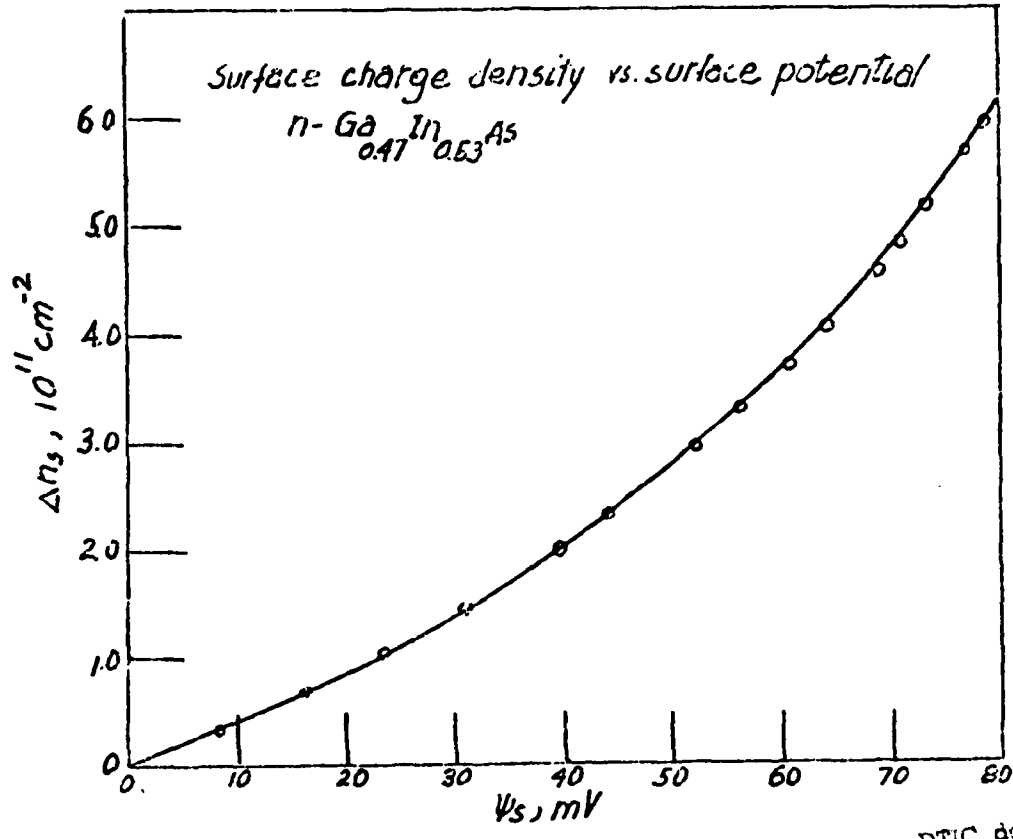


Fig. 7 Calculated dependence of surface potential on free carrier concentration in the accumulation layer using eq. (10).

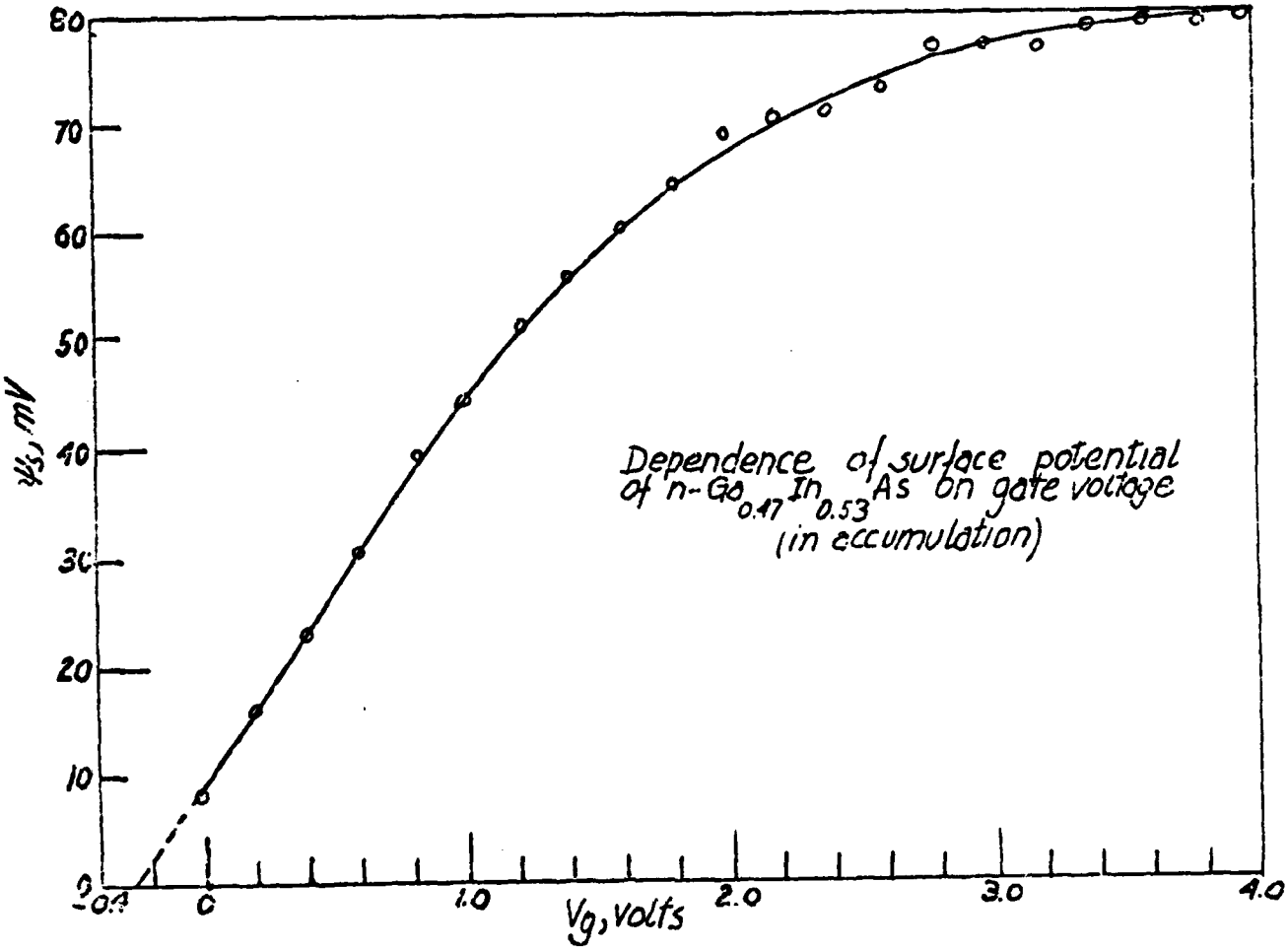
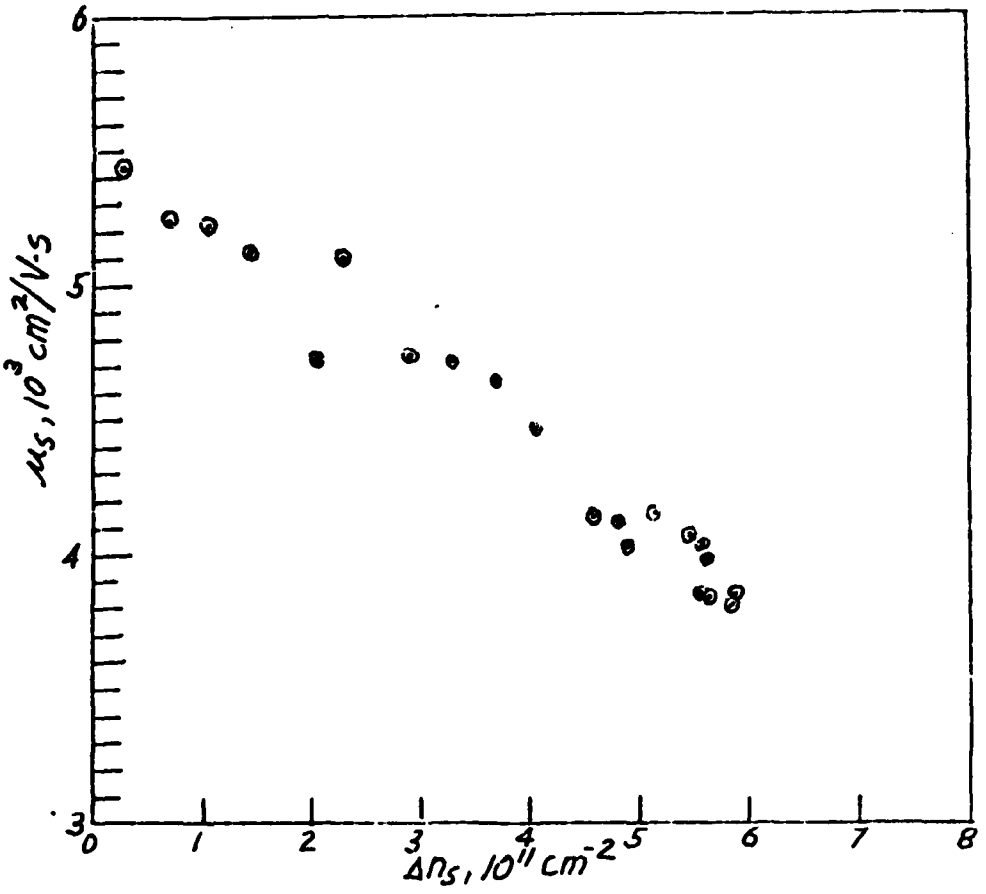


Fig. 8 Dependence of surface potential on gate voltage in accumulation, derived from the experimental measurements.



Electron mobility of surface acc. layer
n-$Ga_{0.47}In_{0.53}As$

Fig. 9 Mobility of electrons in the accumulation as a function of surface charge density calculated by means of eq. (8).

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