

Ohmic contacts to n -GaAs using graded band gap layers of $\text{Ga}_{1-x}\text{In}_x\text{As}$ grown by molecular beam epitaxy

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Ohmic contacts were studied on structures which utilize the fact that for InAs surfaces Fermi level pinning occurs at or in the conduction band. It was found that an epitaxial layer of n - $\text{Ga}_{1-x}\text{In}_x\text{As}$ grown by molecular beam epitaxy on n -GaAs which is graded in composition from $x = 0$ at the GaAs interface to $0.8 \leq x \leq 1.0$ at the surface will produce a structure with a nearly zero Schottky barrier height for the metal- $\text{Ga}_{1-x}\text{In}_x\text{As}$ interface and hence a low resistance ohmic contact. A transmission line measurement of non-alloyed contact resistance of $5 \times 10^{-7} < R_c < 5 \times 10^{-6}$ ohm cm^2 was obtained for a $\text{Ag}/n\text{-Ga}_{1-x}\text{In}_x\text{As}/n\text{-GaAs}$ MESFET structure.

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I. INTRODUCTION

It is well known that low resistance ohmic contacts to n -GaAs are difficult to obtain due to a ≈ 0.8 eV Schottky barrier associated with the metal-GaAs interface. Recently¹ a technique to avoid this problem was developed which utilizes the electron affinity and lattice matched Ge-GaAs heterojunction. In this report, we utilize the fact that Fermi level pinning occurs at or in the conduction band on InAs surfaces, and that Schottky barrier heights for metal contacts to $\text{Ga}_{1-x}\text{In}_x\text{As}$, $0.8 < x \leq 1$, are less than or equal to zero.² Thus, an epitaxial layer of n -type $\text{Ga}_{1-x}\text{In}_x\text{As}$ grown by molecular beam epitaxy on n -type GaAs which is graded in composition from $x = 0$ at the GaAs interface to $0.8 \leq x \leq 1$ at the surface is expected to produce an "ohmic" structure with a nearly zero Schottky barrier height for the metal- $\text{Ga}_{1-x}\text{In}_x\text{As}$ interface and hence a low contact resistance. The advantages of this structure are that post-deposition alloying is not necessary and that with suitably etched structures, low temperature processing with one metallurgy can be used to form source-gate-drain contacts for MESFET devices.

II. THEORY

The metal/ n -GaAs contact can be represented by the energy band diagram of Fig. 1(a). It has been found experimentally for n -GaAs that the Schottky barrier height ϕ_b cannot be represented by the Schottky relationship:

$$\phi_b = \phi_m - X_{sc}$$

where ϕ_b is the barrier height to n -GaAs; ϕ_m is the metal work function and X_{sc} is the electron affinity for the semiconductor. Instead ϕ_b seems to be roughly independent of ϕ_m and has a value of about 0.7–0.9 eV.² This effect has generally been ascribed to Fermi level pinning at the surface or interface due to a large density of mid-gap states either at the surface or interface.³ More recently,⁴ these states have been postulated to be associated with defects in the surface/interface region

which occur as the result of either oxygen adsorption or metal deposition. Whatever the cause, Fermi level pinning causes rectifying current-voltage characteristics for metal contact to n -GaAs: for $n \leq 10^{18} \text{ cm}^{-3}$ this is useful for Schottky diodes; for high doping levels ohmic tunneling behavior results. However, the dynamic resistance of tunneling contacts can be excessively large for some applications such as MESFET's and lasers.

Surface states do not always cause mid-gap Fermi level pinning. For example, surfaces of InAs exhibit pinning in the conduction band.^{5,6,7} Thus, the situation for a metal/ n -InAs contact shown in Fig. 1(b) produces an "ideal" ohmic contact where ϕ_b is ≤ 0 . In this case, tunneling is not required and low resistance contacts can be made for a wide range of n -type doping without need of alloying to form n^+ surface layers. With this in mind one might conclude that good ohmic contacts for GaAs would result if the structure $M/n\text{-InAs}/n\text{-GaAs}$ were used. However, this is not the case and the reason for this is shown in Fig. 1(c). For this structure, there is a positive ϕ_b between the n -InAs and n -GaAs which, depending on the doping level, results in either rectifying or tunneling ohmic contacts. This barrier results from one or more of the following: (a) a large electron affinity discontinuity across the interface, (b) a large lattice constant discontinuity, and (c) a "dirty" GaAs surface prior to epitaxial growth. The effect of the latter two is to produce mid-gap interface states and hence mid-gap Fermi level pinning. Thus, the n -InAs/ n -GaAs abrupt junction behaves like the M/n -GaAs contact of Fig. 1(a). A solution to this problem is shown in Fig. 1(d). For this case, the abrupt n -InAs/ n -GaAs junction is replaced by a layer of $\text{Ga}_{1-x}\text{In}_x\text{As}$ graded in composition from $x = 0$ at the GaAs interface to $x = 1$ at the InAs interface. (Alternatively, the InAs can be omitted entirely and the metal deposited directly on the graded layer. For this case, the surface of the layer can have a composition⁸ $0.8 \leq x \leq 1$). Notice that for Fig. 1(d), there are no abrupt discontinuities in the conduction band and that ϕ_b is ≤ 0 for the M/n -InAs contact. Thus, this structure is expected to produce *non-alloyed low resistance* ohmic contacts.

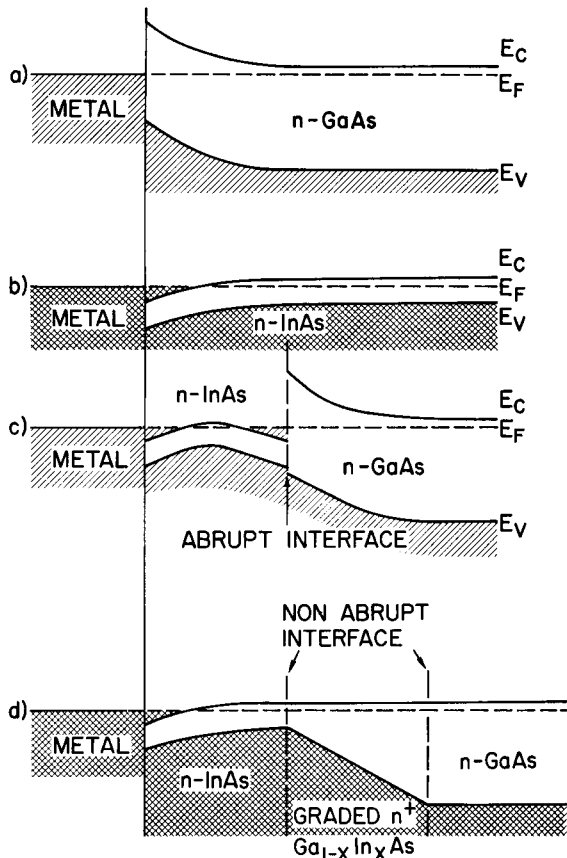


FIG. 1. Band-bending diagram for various semiconductor interfaces. (a) metal on *n*-GaAs, (b) metal on *n*-InAs, (c) metal on *n*-InAs on *n*-GaAs, (d) metal on *n*⁺-InAs on graded *n*⁺-Ga_{1-x}In_xAs on *n*-GaAs.

III. EXPERIMENT

The substrates for the MBE growth were Cr doped GaAs which had resistivity values of $>10^7 \Omega \text{ cm}$. The substrates were prepared for MBE by chemical polishing, cleaning, and etching, and then examined under phase contrast microscopy to check surface topography. The samples were then mounted on Moly heater blocks using In as the contact medium. After mounting, the samples are transferred to the MBE vacuum chamber. Prior to growth, the samples were cleaned thermally by heating in vacuum to 600°C for 5 min. The deposition sources were Ga and In (99.9999 purity) and undoped InAs, used to supply an As_2 flux. The As_2/Ga ratio was ~ 2.5 . The growth rate was $0.3 \mu\text{m/h}$; substrate temperatures were $\sim 550^\circ\text{C}$ for GaAs and $\sim 450^\circ\text{C}$ for InAs.

The structure was fabricated as follows: A 0.5μ layer of Ge-doped *n*-GaAs ($\sim 2 \times 10^{17}/\text{cm}^3$) was deposited directly onto the substrate. A graded layer of 0.25μ thickness, starting at $\text{Ga}_{0.99}\text{In}_{0.01}\text{As}$ and ending with InAs was grown. The donor concentration was raised to $\sim 3 \times 10^{18} \text{ cm}^{-3}$ in the first $0.1 \mu\text{m}$. A layer of Ag ($0.1 \mu\text{m}$) was deposited *in situ*.

The contact resistivity was determined by a standard transmission line type measurement as first described by Schockley.⁹ Unfortunately, the extraction of a value for contact resistance by this technique requires independent characterization of materials parameters appropriate to the $\sim 0.5 \mu$ *n*-GaAs layer. This has not yet been done; the absence of a buffer layer between the substrate and this active layer prevents us from confidently assuming the parameters appropriate to an MBE-grown layer. We can, however, assume "best" and "worst" material parameters, and calculate contact resistance R_c for both cases. This exercise results in the limits

$$5 \times 10^{-7} \Omega \text{ cm}^2 < R_c < 5 \times 10^{-6} \Omega \text{ cm}^2.$$

Clearly, further work needs to be done to better characterize this contact resistance. However, the present results are entirely consistent with the energy diagram shown in Fig. 1(d) and with the theory presented herein. Furthermore, Kajiyama *et al.*⁸ have reported the compositional dependence of ϕ_b upon In concentration in $\text{Ga}_{1-x}\text{In}_x\text{As}$, and it appears likely that this technique can be used to obtain a Schottky barrier height anywhere between that of GaAs ($\sim 0.9 \text{ eV}$) and that of InAs ($\sim 0 \text{ eV}$) with the same metal.

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