Schottky Enhancement of Contacts to n-(In_{0.52}Al_{0.48})As Using PdAl as a Metallization

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INTRODUCTION

Swenson et al.\(^1\) presented a combined thermodynamic/kinetic model based on the exchange mechanism for a reciprocal-equilibrium relationship between four compound components: IIIV, III\(_9\)V, TIII, and TIII\(_9\). The symbols IIIV and III\(_9\)V denote two compound semiconductors, consisting of different Group III elements and a common Group V element (e.g., InAs and AlAs). The symbols TIII and TIII\(_9\) refer to two transition-metal intermetallics that have a common transition-metal element and different Group III elements (e.g., PdIn and PdAl). According to this model, when a metallization TIII reacts with a semiconductor IIIV at the interface, the group III\(_9\) element in the metallization exchanges with the group III element in the semiconductor, forming an interlayer of semiconductor alloy enriched with the III\(_9\) element. It is equivalent to saying that the semiconductor has been enriched in the amount of III\(_9\)V compound because the ternary semiconductor is often thought of as an alloy of two binary-compound semiconductors (IIIV and III\(_9\)V). Enrichment of III\(_9\)V in this interlayer semiconductor alloy may lead to either Schottky or ohmic enhancement depending on the Schottky barrier height’s dependence on the semiconductor substrate’s III’V composition. The basic idea of this model has been presented previously.\(^2\)–\(^5\)

Subsequently, Chen et al.\(^6\) used a series of pseudobinary alloys of NiAl and NiGa, or Ni(Al\(_{1-x}\)Ga\(_x\)), as metallizations to n-GaAs. The mole fractions of NiAl in these alloys were varied from (1\( - x\)) = 0.25 to 1 at equal composition intervals. They found that the Schottky barrier height of the rapid thermal anneal (RTA)-treated Ni(Al\(_{1-x}\)Ga\(_x\))/n-GaAs contacts at 400°C indeed increased with the mole fraction of NiAl in the metallizations. When pure NiGa is used, which is thermodynamically stable on GaAs, the Schottky barrier height of the contact remained the same, irrespective of the annealing temperature. On the other hand, when an alloy of NiAl and NiGa is used as the metallization, the Schottky barrier heights of the resulting contacts are enhanced when annealed and moreover increase with increasing NiAl content in the as-deposited alloy. These results are consistent with the prediction of the combined thermodynamic/kinetic model of Swenson et al.\(^1\)

The (In_{0.52}Al_{0.48})As is a compound semiconductor with a bandgap of 1.46 eV that is lattice-matched to InP. It is used to fabricate a wide range of semiconductor devices including high-electron mobility transistors, heterojunction bipolar transistors, and...
photodetectors. As device dimensions continue to shrink, the requirement for such devices will continue to become more stringent. Application of the combined thermodynamic/kinetic model presented previously can lead to significant improvements in metal-semiconductor contact technology because this type of understanding and subsequent control over the system’s interfacial characteristics can be used to tailor the electrical properties of the contact. The combined thermodynamic/kinetic model that was used in the study of intermetallic-alloy metallizations on pure III-V semiconductors, as previously described, can be applied to intermetallic metallizations on the interesting ternary \((\text{In}_{0.52}\text{Al}_{0.48})\text{As}\) as well. In the present study, we employ a pure binary-intermetallic compound, PdAl, as a reactive metallization to the n-type ternary-semiconductor alloy consisting of 52-mol. % InAs and 48-mol. % AlAs. According to this model, PdAl should enhance this semiconductor’s Schottky barrier height in a similar manner as Ni(Al\(_{1-x}\text{Ga}_x\)) to n-GaAs, provided a suitable reciprocal-phase relationship exists in the InAs-ALAs-PdAl-PdIn system. A true reciprocal system is not possible in the present case because PdAl and PdIn do not have the same crystal structure,\(^7\) but the existence of a quasi-reciprocal system will be satisfactory for the application of the present model, as will be discussed.

**EXPERIMENTAL METHOD**

To establish the phase-diagram of the InAs-ALAs-PdAl-PdIn system, it is essential to know the phase diagrams of the six constituent-binary and four constituent-ternary systems. Phase diagrams of the six binaries Al-As, Al-In, Al-Pd, As-In, As-Pd, and In-Pd are known. Isothersms for two of the four ternaries, Al-As-In\(^5\) and As-In-Pd\(^9,10\) are also found in literature.

To determine the major features of the phase diagrams for the other two ternaries Al-As-Pd and Al-In-Pd, phase diagram samples were made in the regions of interest for this study. Sample pellets were made by cold pressing proper weight ratios of elemental-metal powders for the desired alloy compositions. Each of the pellets was placed in an alumina tube, which was then placed in a quartz ampoule. The ampoules were then evacuated to below \(10^{-2}\) torr and sealed. Once sealed, the samples were equilibrated by annealing for 2 months either at 600°C or 640°C. Metallography, x-ray diffraction, and electron probe microanalysis (EPMA) were all used to verify the sample compositions and further characterize the quality of the alloys. For Al-As-Pd phase-diagram samples, appropriate mixtures were made of Pd, AlAs, Al, PdAl\(_2\), PdAl, and PdAs\(_2\) powders, all with purity 99.99% or better. Elemental metals were used as the starting materials for Al-In-Pd phase-diagram samples.

Electrical contacts were fabricated to experimentally determine the Schottky barrier heights of PdAl on n-(In\(_{0.52}\text{Al}_{0.48}\))As. Samples used for electrical measurements consisted of 630-nm epitaxial \((\text{In}_{0.52}\text{Al}_{0.48})\text{As}\) grown on S-doped InP. To determine the carrier concentration of the \((\text{In}_{0.52}\text{Al}_{0.48})\text{As}\) layer, a 630-nm unintentionally doped-(In\(_{0.52}\text{Al}_{0.48}\))As layer was grown on a 60-nm, undoped-InP buffer layer for Hall measurement. The epilayer was found to be n-type with a carrier concentration of \(2 \times 10^{16}\) cm\(^{-3}\). AuGe was evaporated onto the back of the conductive InP substrate to form an ohmic contact, which is necessary for measurement of the electrical properties of the Schottky contact on the top of the semiconductor wafer.

The semiconductor substrates were degreased with trichloroethylene, acetone, and methanol in a warm ultrasonic bath and then rinsed in flowing deionized water. After the rinse, standard lift-off photolithographic techniques were used to pattern 400-μm-diameter pads. The surface oxide of the patterned substrates was removed by etching in a 5% \(\text{NH}_4\text{OH}\) solution at 4°C for 1 min, and the wafers were then immediately loaded into a vacuum chamber with a pressure lower than \(10^{-7}\) torr.

Nominally 120-nm-thick PdAl films were deposited onto the patterned substrates by direct-current magnetron sputtering from a single alloy target. This PdAl alloy for the target was fabricated by arc melting high-purity Pd and Al. The resulting alloy slug was then ground into a fine powder and hot-pressed into a 2-in. sputtering target. EPMA showed that the composition of the sputtered PdAl films was slightly Pd-rich, which is desirable because the \(\beta\)'-PdAl phase is only stable between 51 at.% and 52 at.% Pd at the temperatures encountered in our experiments. Specifically, the \(\beta\)'-PdAl metallization is necessary to participate in the exchange reaction when deposited on the \((\text{In}_{0.52}\text{Al}_{0.48})\text{As}\) substrate. After sputter deposition, the photoresist was lifted off in an acetone bath, leaving the patterned metallization. The RTA heat treatments of the samples were performed in an AG Associates MiniPulse RTA system using a flowing-argon atmosphere. The barrier heights of the as-deposited and annealed contacts were measured at room temperature using both the capacitance-voltage (C-V) and current-voltage (I-V) methods.

To characterize the interface reaction occurring as a result of annealing, conventional transmission electron microscopy (TEM) and high-resolution transmission electron microscopy (HRTEM) were used. The same procedure as described previously, with the lithography steps omitted, was used to prepare the PdAl/(In\(_{0.52}\text{Al}_{0.48}\))As TEM samples. After the appropriate RTA treatment, the TEM specimens were fabricated by thinning the wafers to electron transparency, using a combination of mechanical polishing and ion milling. Electron microscopy was conducted in a JEOL 200CX electron microscope (Japan Electron Optics Ltd., Tokyo) and a Philips CM200 high-resolution microscope (Philips Electronic Instruments Corp., Mahwah, NJ).