PdAl Schottky contact to $In_{0.52}Al_{0.48}As$ grown by metalorganic chemical vapor deposition

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β-PdAl was studied as a Schottky contact to metalorganic chemical vapor deposition grown $In_{0.52}Al_{0.48}As$. Intermetallic alloy β-PdAl was chosen in order to utilize the Al–In exchange reaction which may occur between PdAl and $In_{0.52}Al_{0.48}As$, which would result in an enhanced Schottky barrier height. *I–V*, *C–V*, and deep level transient spectroscopy (DLTS) were used to determine the contact characteristics. The contact barrier height (ϕ_b) was measured by *I–V* and *C–V* methods after different annealing conditions, and good agreement between *I–V* and *C–V* results were obtained. The largest ϕ_b value is 0.67 eV from *I–V* measurement (0.69 eV from *C–V*) after the diode was annealed at 450 °C for 1 min. DLTS measurements were carried out to examine the effect of deep traps in the $In_{0.52}Al_{0.48}As$ layer. Two deep levels were found, but the concentrations are lower than the intrinsic donor concentration obtained from the Hall method. The activation energies for these two deep levels obtained from an Arrhenius plot are 0.38 and 0.65 eV, respectively. © *1995 American Institute of Physics.*

Schottky contacts are widely used in semiconductor devices such as metal field effect transistors, solar cells, and high electron mobility transistors (HEMTs). Recently, 305 GHz cutoff frequency and low noise performance have been achieved by a prototype $In_{0.52}Al_{0.48}As/In_{0.53}Ga_{0.47}As/InP$ HEMT using a Schottky metal/$In_{0.52}Al_{0.48}As$ contact (Ti/Pt/Au) as the gate material.[1] In this HEMT, semiconductor $In_{0.52}Al_{0.48}As$, with a direct energy band gap of 1.46 eV, is used as the barrier layer. This alloy semiconductor is lattice matched to the other two semiconductors; $In_{0.53}Ga_{0.47}As$ and InP, that have energy band gaps of 0.77 and 1.35 eV, respectively. Since the HEMT performance can be improved by increasing Schottky barrier height (ϕ_b) of the gate contact to $In_{0.52}Al_{0.48}As$,[2] it is desirable to enhance the barrier height to this compound semiconductor alloy.

One of the techniques used to enhance this barrier height relies on the increase in the Al composition of $In_xAl_{1-x}As$ above $1-x=0.48$. Recently, Lin *et al.*[3] have reported that ϕ_b of Au contact increased with Al content of $In_{1-x}Al_xAs$. For $In_{0.52}Al_{0.48}As$, the use of a contact material which reacts with the semiconductor alloy at the interface to exchange the In atoms for Al atoms could also be used to enhance the Schottky barrier height due to the increase of the Al composition immediately adjacent to the semiconductor. Chen *et al.*[4] have recently found that the Schottky barrier of β-NiAl/GaAs can be enhanced by rapid thermal annealing (RTA) at high temperatures. This enhancement is due to a Ga–Al exchange reaction to form a thin layer of (Ga,Al)As at the interface. Therefore, it is desirable to seek a contact material which may react with the alloy semiconductor, $In_{0.52}Al_{0.48}As$, to form a thin layer of alloy with higher Al concentration, leading to an increased Schottky barrier height.

β-PdAl was selected as a contact material for this possible Al–In exchange reaction after a review of the phase equilibria of several transition metal In–Al–As systems. Both β-NiAl and β-PdAl have the same ordered bcc (or CsCl) structure. Although the phase equilibria of PdAl–PdIn–InAs–AlAs are not known, it is possible that a reciprocal system may exist similarly to that of NiAl–NiGa–GaAs–AlAs. It is the existence of this reciprocal system which leads to an enhanced Schottky barrier height of the β-NiAl/GaAs contacts after RTA at high temperatures. The purpose of present study is to determine the Schottky contact characteristics of β-PdAl/$In_{0.52}Al_{0.48}As$. Barrier heights of annealed contacts were measured at room temperature using the current–voltage (*I–V*) and capacitance–voltage (*C–V*) methods. The effect of deep traps in the $In_{0.52}Al_{0.48}As$ layer was examined by using deep level transient spectroscopy (DLTS).

Schottky diodes prepared for the electrical measurements have a basic structure of PdAl/$In_{0.52}Al_{0.48}As$/InP/AuGe. The $In_{0.52}Al_{0.48}As$ epitaxial layer was grown by a metalorganic chemical vapor deposition (MOCVD) method using S-doped InP substrate and TMA (trimethyl-aluminum), TMI (trimethyl-indium), high purity arsine, and TBP (tertiary-butylphosphine) as source materials.[5] An undoped $In_{0.52}Al_{0.48}As$ layer of 0.63 μm thick was grown at 650 °C after a 0.06 μm thick undoped InP layer was grown as a buffer on an InP substrate. Carrier concentration of the $In_{0.52}Al_{0.48}As$ layer was measured by the Hall effect method. After the growth, AuGe was evaporated onto the backside

InP substrate, which formed an Ohmic contact after annealing at 360 °C for 1 min in an AG Associate Mini Pulse rapid thermal annealing (RTA) system under a flowing Ar gas. The wafer was then degreased with trichloroethylene (TCE), acetone, methanol, then rinsed with DI water, and blown dry with N_2 gas.

For the fabrication of the β-PdAl Schottky contact, a standard photolithography technique was used to define pad patterns of 440 μm diam. The patterned wafer was then etched in 5% NH_4OH solution at 4 °C for 1 min to remove any native oxide on the $In_{0.52}Al_{0.48}As$ surface. The etched wafer was immediately loaded into a vacuum chamber with pressure lower than 1×10^{-7} Torr. Nominally 30 Å Pd was first sputtered onto the wafer for residual oxide penetration.[6] A 1200 Å layer of the Schottky contact material PdAl was then sputtered from a PdAl alloy target. After the deposition, the remaining photoresist used during the photolithography was removed by liftoff with acetone. The sputtered PdAl was characterized by x-ray diffraction and electron probe microanalysis (EPMA) to identify the crystal structure and compositions. Two sets of diodes were then annealed at 350 and 450 °C, respectively, for 1 min in the same RTA system.

After the diode formation, *C–V* and *I–V* measurements were carried out to evaluate the barrier height value of the Schottky contact. For *I–V* measurement the following equations are important:[7]

$$I = aA^*T^2 \exp(-e\phi_b/kT)[\exp(eV/nkT)-1], \quad (1)$$

$$A^* = 4e\pi m^* k^2/h^3, \quad (2)$$

where a is the contact area, V is the applied bias, A^* is the Richardson constant, m^* is the effective electron mass of $In_{0.52}Al_{0.48}As$, ϕ_b is the Schottky barrier height, and n is the ideality factor, indicating the dominant current transport mechanism. For this calculation, the value of A^* is taken to be 9.24 for m^*/m_0 equal to 0.077.[8] To confirm this value, variable temperature *I–V* measurement was carried out and

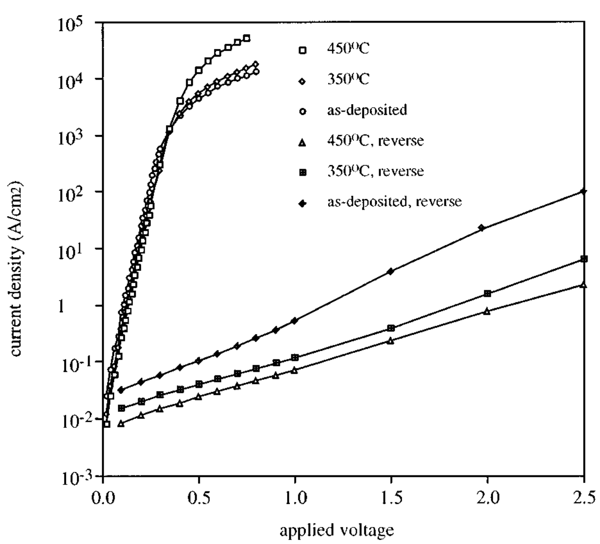

FIG. 1. The *I–V* characteristics of PdAl contact to $In_{0.52}Al_{0.48}As$ shows an increase of Schottky barrier height from 0.60 to 0.67 eV after the contact was annealed at 450 °C for 1 min.

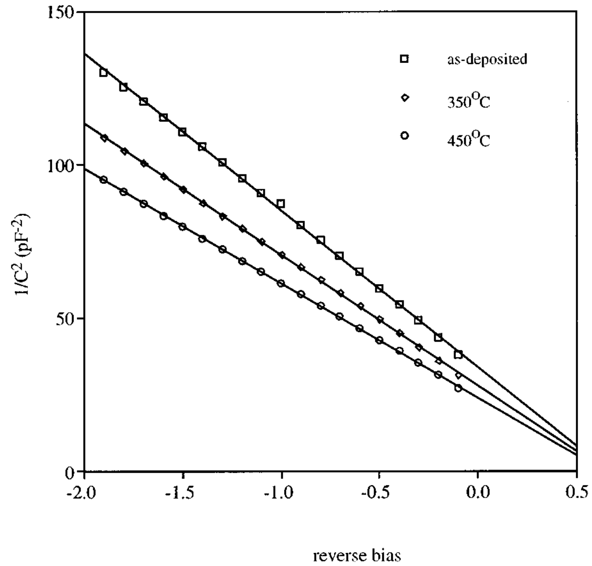

FIG. 2. The *C–V* characteristics of PdAl contact to $In_{0.52}Al_{0.48}As$ shows an increase of Schottky barrier height from 0.60 to 0.69 eV after the contact was annealed at 450 °C for 1 min.

A^* was calculated from the slope of semilog $I/T^2-1/T$ plot. n was determined from the measured I and V data which were plotted on a semilog scale using $n=\{kT/ed[\ln(I)]/dV\}^{-1}$. The subsequent values of ϕ_b were then determined from Eq. (1).

For *C–V* measurement, ϕ_b was determined by measuring the capacitance of diodes as functions of reverse voltage, then applying the equation:

$$C^{-2} = 2(\phi_b + V_r - kT/e)/a^2 e N_d \mathscr{E}s, \quad (3)$$

where C is the capacitance, N_d is the intrinsic doping concentration, $\mathscr{E}_s$ is the permittivity of $In_{0.52}Al_{0.48}As$, and V_r is the reverse bias. $1/C^2$ and V_r data were plotted on a linear scale and ϕ_b values were determined from the intercept on the V_r axis.

Deep level transient spectroscopy (DLTS) was also used on these structures to examine the influences of thermal annealing on the electrical properties of the diodes. This method provided information about the emission energy and concentrations of the deep traps in the near-surface region of the processed semiconductor.

Results of the measured *I–V* and *C–V* data are shown in Figs. 1 and 2, and the values of ϕ_b and n are listed in Table I. These data show good agreement between *I–V* and *C–V* results. The values of the ideality factor (n) are close to one, indicating that thermionic emission is the dominant current transport mechanism. These data indicated that ϕ_b increases

TABLE I. The ideality factors, ϕ_b determined from *I–V* and *C–V* measurements for PdAl contact to $In_{0.52}Al_{0.48}As$.

	n	ϕ_b (*I–V*)	ϕ_b (*C–V*)
As-deposited	1.1	0.6	0.6
350 °C 1 min	1.11	0.64	0.66
450 °C 1 min	1.09	0.67	0.69

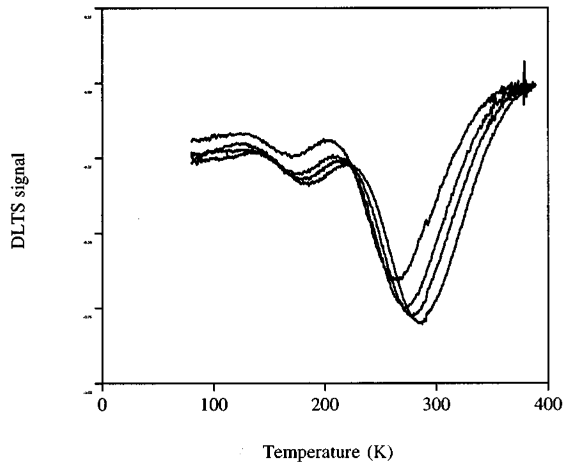

FIG. 3. DLTS spectra at four different rate windows of PdAl contact to $In_{0.52}Al_{0.48}As$ annealed at 450 °C for 1 min.

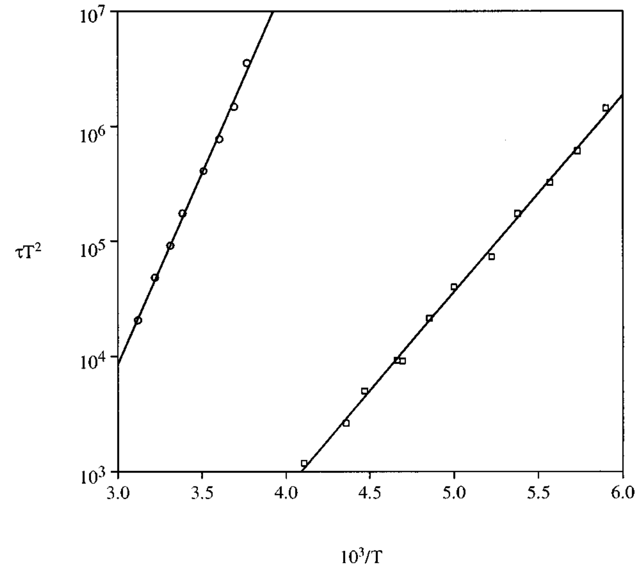

FIG. 4. Arrhenius plots of deep levels in the $In_{0.52}Al_{0.48}As$ layer annealed at 450 °C for 1 min.

with annealing temperature, suggesting that the Al–In exchange reaction may have occurred. X-ray diffraction and EPMA results show that the sputtered PdAl is a β phase with Pd composition close to the data obtained from the literature.[9] The existence of a reciprocal system PdAl–PdIn–InAs–AlAs is therefore likely. It is expected that longer annealing times or higher annealing temperatures should further enhance the Schottky barrier height.

While ϕ_b was increased by rapid thermal annealing, DLTS results show no change between the as-deposited and annealed samples. The DLTS spectra at four different rate windows for a diode annealed at 450 °C for 1 min is presented in Fig. 3. Diodes annealed at other conditions show similar results. According to the spectra, at least two deep levels exist in the epitaxial $In_{0.52}Al_{0.48}As$ layer. Two emission energy levels were determined as 0.38 and 0.65 eV from an Arrhenius plot of the measured data, as shown in Fig. 4. These values are close to Schramm's work.[10] The concentrations of these deep levels are 5×10^{14} and 1×10^{15} cm^{-3}, respectively. These values are much smaller than the intrinsic donor concentration, which is 2×10^{16} cm^{-3} measured by the Hall method. Therefore, the thermal annealing processes have no effect on the electrical properties at the near-surface region of the $In_{0.52}Al_{0.48}As$ layer.

In summary, we have sputtered β-PdAl on $In_{0.52}Al_{0.48}As$ as a Schottky contact material to enhance the barrier height. The barrier height is increased from 0.6 eV to 0.67 (*C–V* 0.69) eV after the diode was annealed at 450 °C for 1 min. Two deep levels were found from DLTS measurements, but the concentrations are lower than the intrinsic donor concentration.

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