Transparent and opaque Schottky contacts on undoped $In_{0.52}Al_{0.48}As$ grown by molecular beam epitaxy

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The Schottky barrier height was measured for five different materials on undoped $In_{0.52}Al_{0.48}As$ grown by molecular beam epitaxy (MBE). Of the materials tested, two were transparent conductors, indium-tin-oxide (ITO), and cadmium tin oxide (CTO) and for comparison, three were opaque metals (Au, Ti, and Pt). The barrier heights were measured using *I–V* measurements. Due to the high series resistance created by the undoped $In_{0.52}Al_{0.48}As$, the Norde method [J. Appl. Phys. **50**, 5052 (1979)] was used to plot the *I–V* characteristics and extract the Schottky barrier height. The Schottky barrier heights were determined to be 0.639, 0.637, 0.688, 0.640, and 0.623 eV for ITO, CTO, Au, Ti, and Pt, respectively. Previously published results for Schottky barriers on $In_{0.52}Al_{0.48}As$ are compared with our measurements. © *1995 American Institute of Physics.*

$In_xAl_{1-x}As$ is a useful wide band-gap semiconductor material for microwave devices such as modulation-doped field-effect transistors (MODFET),[1–4] and optoelectronic devices such as photodetectors.[5–7] A thin layer of wide band-gap $In_{0.52}Al_{0.48}As$ (50–1000 Å) is often grown above an $In_{0.53}Al_{0.47}As$ active layer to raise the Schottky barrier height and significantly reduce leakage currents. Researchers have focused on $In_{0.52}Al_{0.48}As$ ($E_g = 1.456$ eV), the lattice constant of which is matched to InP and $In_{0.53}Ga_{0.47}As$. Both transparent [e.g., indium-tin-oxide (ITO) and cadmium tin oxide (CTO), etc.] and opaque (e.g., Au, Ti, Pt, etc.) contacts have been used to form Schottky contacts[2–3,6–8] on $In_{0.52}Al_{0.48}As$. The characteristics of these $In_{0.52}Al_{0.48}As$ Schottky barriers have been investigated extensively since the last decade.[2,9–11]

Reliable Schottky barrier formation is always a big issue, and is one of the oldest problems which still has not been solved.[12] As InGaAs/InAlAs MODFETs became popular, extensive research was focused on the Schottky issues of metals on InAlAs as they related to MODFET performance. Previous investigations of the barrier heights of various metals on $In_{0.52}Al_{0.48}As$ have been based on opaque contacts only, such as Au, Ti, Pt, etc.[2,9–11,13–18] (see Table I). However, to improve the responsivity of metal-semiconductor-metal (MSM) photodetectors, CTO and ITO have been used as transparent electrodes[6–8] but the Schottky barrier properties of these transparent materials have not been systematically investigated, and the Schottky barrier height plays a key role in the dark current and therefore performance of a MSM photodetector. In this letter, we present a study and comparison of the Schottky barrier heights of five different transparent and opaque contacts, CTO, ITO, Au, Ti, and Pt on a bulk undoped $In_{0.52}Al_{0.48}As$ layer grown by molecular beam epitaxy (MBE). Table I lists previously published related results of Schottky barrier heights on $In_{0.52}Al_{0.48}As$ for comparison.

An undoped 2 μm thick $In_{0.52}Al_{0.48}As$ layer was grown on an n^+-InP substrate at 550 °C using MBE. A highly Si-doped (1×10^{18} cm^{-3}) superlattice of InGaAs and InAlAs was employed as a buffer. The unintentionally doped $In_{0.52}Al_{0.48}As$ layer was semi-insulating. Schottky diodes with 1 mm diameters were fabricated using optical photolithography. An *n*-type Ohmic contact was formed on the backside using Au–Ge/Ni/Ti/Au metallization.

Prior to deposition, the surface was treated with $NH_4OH:H_2O$ (1:10) for 30 s. The metal contacts Au, Ti, and Pt were evaporated using an *e*-beam evaporator under high vacuum (2×10^{-6} Torr). The CTO contacts were reactively sputtered at room temperature in a magnetron sputtering system at a total pressure of 2×10^{-2} Torr and with a partial pressure of oxygen of 1×10^{-7} Torr. The resistivity of the 1500–1800 Å thick CTO was measured to be $\rho=2.3\times10^{-4}$ Ω cm. The ITO contacts were reactively deposited using an *e*-beam evaporator with a base pressure of 1×10^{-4} Torr and an overpressure of oxygen on the heated sample held at 175 °C. The resistivity of the 1200 Å thick ITO layer was measured to be $\rho=1.2\times10^{-3}$ Ω cm.

Figure 1 shows the forward *I–V* curves of the different contacts measured using an HP 4142B Modular DC Source/Monitor controlled by HP ICCAP software on a SUN workstation. Since the epitaxial layer is undoped, the *I–V* curves show an excessive series resistance. An undoped $In_{0.52}Al_{0.48}As$ layer was studied to mimic the undoped $In_{0.52}Al_{0.48}As$ which is employed in conventional MODFETs and MSM photodetectors. The conventional *I–V* method to derive the saturation current I_s, and determine the Schottky barrier height does not work under these circumstances. Here the Norde method[19] was used to plot the $F-V$curve to overcome the series resistance problem.

The *F(V)* function is defined as [19]

$$F(V)=\frac{V}{2}-\frac{kT}{q}\ln\left(\frac{I(V)}{SA^{**}T^2}\right) \tag{1}$$

where $I(V)$ is from the *I–V* curve, k is the Boltzmann's constant, q is the electronic charge, h is Planck's constant, S

TABLE I. Schottky barrier heights for *n*-type $In_{0.52}Al_{0.48}As$.

Material	*I–V* measurement	*C–V* measurement	Internal photoemission
Au	$\phi_{Bn}=0.53$ eV[9], *n*-type $\phi_{Bn}=0.699$ eV[13,14], $n=2.4\times10^{16}$ cm^{-3} $\phi_{Bn}=0.72$ eV[13], residual, 0.1-1×10^{16} cm^{-3} $\phi_{Bn}=0.50$ eV[11], MOCVD, 650 °C $\phi_{Bn}=0.60$ eV[11], MOCVD, 710 °C $\phi_{Bn}=0.688$ eV (this work), undoped/semi-insulating	$\phi_{Bn}=0.82$ eV[10], Si doped $1-2\times10^{18}cm^{-3}$ $\phi_{Bn}=0.730$ eV[14], $n=2.4\times10^{16}$ cm^{-3}	$\phi_{Bn}=0.64$ eV[9], at 30 K, *n*-type
Pt	$\phi_{Bn}=0.725$ eV[13,14], $n=2.4\times10^{16}$ cm^{-3} $\phi_{Bn}=0.72-0.75$ eV[4], $n=$mid-10^{16} cm^{-3} $\phi_{Bn}=0.62$ eV[11], MOCVD, 650 °C $\phi_{Bn}=0.69$ eV[11], MOCVD, 710 °C $\phi_{Bn}=0.623$ eV (this work) undoped/semi-insulating	$\phi_{Bn}=0.775$ eV[14], $n=2.40\times10^{16}$ cm^{-3} $\phi_{Bn}=0.76$ eV[4], $n=$mid-10^{16} cm^{-3} $\phi_{Bn}=0.82$ eV[15], $n=1.9-2.4\times10^{17}$ cm^{-3}	
Ti	$\phi_{Bn}=0.655$ eV[13,14], $n=2.4\times10^{16}$ cm^{-3} $\phi_{Bn}=0.68$ eV[16], $n=8.3\times10^{15}$ cm^{-3} $\phi_{Bn}=0.66-0.69$ eV[4], $n=$mid-10^{16} cm^{-3} $\phi_{Bn}=0.6$ eV[17], $n=5\times10^{16}-1\times10^{18}$ cm^{-3} $\phi_{Bn}=0.640$ eV (this work), undoped/semi-insulating	$\phi_{Bn}=0.685$ eV[14], $n=2.60\times10^{16}$ cm^{-3} $\phi_{Bn}=0.59$ eV[15], $n=1.9-2.4\times10^{17}$ cm^{-3} $\phi_{Bn}=0.72-0.73$ eV[4], $n=$mid-10^{16} cm^{-3} $\phi_{Bn}=0.7-0.8$ eV[17], $n=5\times10^{16}-1\times10^{18}$ cm^{-3}	
ITO	$\phi_{Bn}=0.639$ eV (this work), undoped/semi-insulating		
CTO	$\phi_{Bn}=0.637$ eV(this work), undoped/semi-insulating		

is the area, T is the temperature in degrees Kelvin, and A^{**} is the effective Richardson constant, where

$$A^{**}=\frac{4\pi m^{*}qk^{2}}{h^{3}}=\frac{m^{*}}{m_{0}}120\ \text{A cm}^{-2}\ \text{K}^{-2}. \tag{2}$$

For InAs and AlAs, the electron effective masses are $0.023m_0$ and $0.15m_0$, as given by Palic *et al.*[20] and Stukel *et al.*,[21] respectively. Using these values, Vegard's law yields $m_e^{*}=0.084m_0$ for $In_{0.52}Al_{0.48}As$, corresponding to $A^{**}=10.1$ A cm^{-2} K^{-2}. Once the minimum of the F vs V plot is determined, the Schottky barrier height can be obtained using

$$\phi_B=F(V_0)+\frac{V_0}{2}-\frac{kT}{q}, \tag{3}$$

where $F(V_0)$ is the minimum point of $F(V)$, and V_0 is the corresponding voltage. Figure 2 shows the $F-V$ curves of the different contacts. From the plots, the Schottky barrier heights were determined to be 0.637, 0.639, 0.688, 0.640, and 0.623 eV for CTO, ITO, Au, Ti, Pt contacts, respectively. As a comparison, Table I lists the published data of Schottky barrier heights for *n*-type $In_{0.52}Al_{0.48}As$ on related contacts from different authors.

From these results, we found that the barrier height (ϕ_{Bn}) is almost independent of the contact material, even for the conducting oxide CTO and ITO contacts. We believe this is because the Fermi level at the semiconductor surface is pinned, which could be caused by deep level electron traps. Whitney *et al.*[22] did capacitance transient analysis of a doped $(2-3\times10^{16}cm^{-3})$*n*-type $In_{0.52}Al_{0.48}As$ sample and found the dominant electron traps were at 0.39, 0.50, 0.58, and 0.61 eV activation energies with densities higher than $10^{15}cm^{-3}$. Using DLTS, Hong *et al.*[23] found the most significant electron traps with activation energies of 0.56, 0.60, and 0.71 eV and densities above 10^{15} cm^{-3}, and the 0.60 eV trap was independent of the doping level. Naritsuka *et al.*[24] studied undoped $In_{0.52}Al_{0.48}As$ grown by metal-organic chemical vapor deposition (MOCVD) at 625 and 700 °C, and found the activation energy of the dominant deep level was 0.5 eV with a density of order 10^{17} cm^{-3}.

The differences in ϕ_{Bn} for various contacts could be related to defects formed near the metal-semiconductor interface during deposition of the contacts,[12,15] if the Fermi level is pinned by charged defects at the semiconductor-metal interface as proposed by Spicer *et al.*[26] and Zur *et al.*[27] Therefore, various metal-semiconductor schemes could induce a unique defect layer with its own unique barrier height.

In most device applications, Schottky contacts are formed on undoped semiconductor layers. For this reason, we used an undoped layer for this study. However, the *C–V* method cannot be used to measure the Schottky barrier

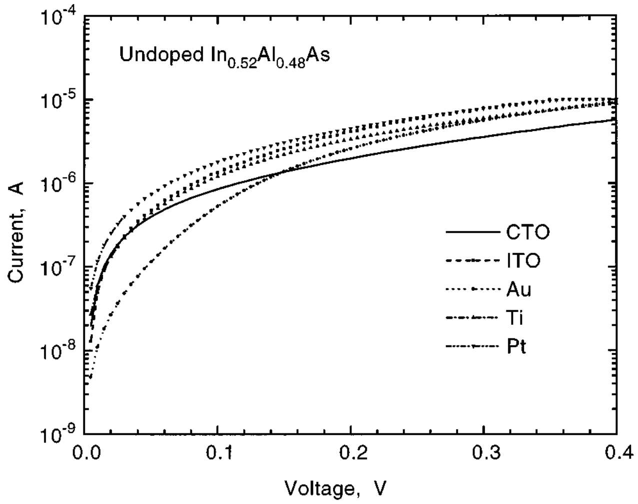

FIG. 1. The forward *I–V* curve of CTO, ITO, Au, Ti, and Pt contacts on undoped $In_{0.52}Al_{0.48}As$ grown by MBE at 550 °C.

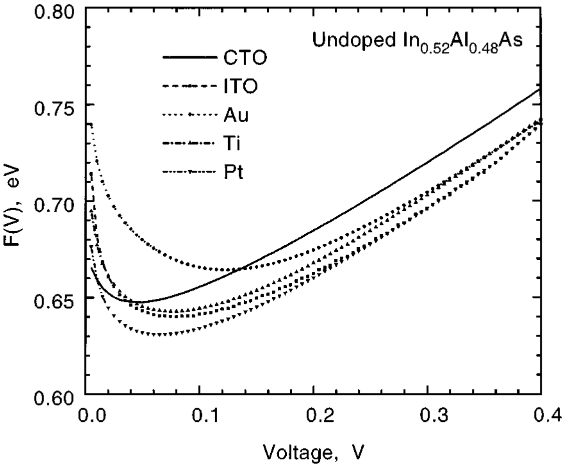

FIG. 2. The $F-V$ curve (Ref. 19) of CTO, ITO, Au, Ti, and Pt contacts on undoped $In_{0.52}Al_{0.48}As$ grown kby MBE at 550 °C.

heights in this situation due to the low carrier concentration. At low bias the undoped layer is fully depleted and shows no modulation of capacitance within the region of interest.

In this letter, we have studied the Schottky barrier heights of five different contacts on MBE grown $In_{0.52}Al_{0.48}As$, which include the opaque contacts Ti, Pt, Au, and transparent contacts ITO and CTO. All the contacts, both transparent and opaque, showed barrier heights which were independent of the material used for the Schottky contact, suggesting that Fermi level pinning was occurring.

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