Optically Transparent ITO Emitter Contacts in the Fabrication of InP/InGaAs HPT's

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Abstract—**An optically transparent emitter InP/InGaAs heterojunction phototransistor (HPT) fabricated using Indium Tin Oxide (ITO) as the ohmic contact is presented for the first time; these devices show similar electrical characteristics to their opaque emitter counterparts and enhanced optical responsivities (5.4 A/W at 780 nm wavelength). Measured spectral response suggests responsivities of up to 30 A/W and 22 A/W at $\lambda = 1310$ nm and 1550 nm respectively.**

I. Introduction

With the demonstrated advantages of an optical fiber telecommunication system over a conventional copper-wire based system, the efficient conversion of an electrical signal to an optical signal and vice versa, is now of utmost importance. Similarly, rapid progress in semiconductor materials growth technology and emergence of novel techniques in device fabrication has led to a continual improvement in the performance of opto-electronic integrated circuits (OEIC's). Hence, renewed interest in using phototransistors as detectors has been aroused world wide, particularly with Heterojunction Bipolar Transistors (HBT's). Studies using such HBT's with opaque emitter contacts show excellent suitability of these devices as photodetectors in terms of optical performance where signal to noise ratios in excess of 30 dB have been obtained [1]–[3]. The optical gain of any phototransistor depends on the coupling efficiency, the collection efficiency and its internal gain; in the HPT structure, there lies an inherent trade-off between the speed and the collection efficiency. However, by using a transparent emitter contact, the coupling efficiency can be significantly improved thereby raising the overall gain-bandwidth of the device correspondingly.

HBT's fabricated using the InP/InGaAs material system has numerous advantages over its GaAs/AlGaAs counterpart; from a telecommunications application point of view most important of these is the bandgap of InGaAs (0.75 eV) which is sensitive to 1.3 μm and 1.55 μm radiation—wavelengths corresponding to the low fiber loss windows and almost unanimously used in longhaul cables [4]. In addition to this, we have recently shown that the InP/InGaAs HBT's exhibit a lower turn on voltage (0.2 eV) than GaAs-based HBT's (0.8 eV) [5]. This clearly demonstrates the advantage of InP-based HBT's for low power circuit applications, such as in mobile telecommunications.

In this paper we report the usage of Indium Tin Oxide (ITO) for the first time as the transparent ohmic contact to the emitter of such an InP/InGaAs HPT, following our similar work earlier on AlGaAs/GaAs HPT's. A transparent contact overcomes the processing difficulties asscociated with opaque ring electrodes where near micron structures need to be fabricated. ITO is a degenerate semiconductor itself and is a practically transparent and electrically conductive material [6]. Aside from its numerous diverse applications, we have recently used ITO to make both schottky and ohmic contacts to photodetectors, transparent gate High Electron Mobility Transistors (TG-HEMT's) and Vertical Cavity Surface Emitting Lasers (VCSEL's) [7]–[9].

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II. Experimental Details

A. ITO Deposition

A Nordiko 1500 r.f. sputtering machine was used to sputter ITO from a hot pressed target (4″ diameter, 90% In_2O_3+ 10% SnO_2) in an Ar/O_2 plasma. The following sputtering conditions were kept constant: base pressure = 1×10^{-6} torr, total pressure during sputtering = 5×10^{-3} torr and deposition time = 1 hr. The r.f. power and the oxygen partial pressures were varied to study their effects on the sheet resistance of the ITO films. These were varied as follows: r.f. power between 100 W and 200 W and the oxygen partial pressure between 7 $\times 10^{-3}$ and 1.4 $\times 10^{-2}$. Our results from depositions using a oxygen partial pressure of 12 $\times 10^{-3}$ showed that the sheet resistances of the ITO films were inversely proportional to the exponential of the RF power used; films grown at 100 W showed typical R_{sh} of about 70 k$\Omega/\square$, at 150 W this was 4 k$\Omega/\square$ while at 200 W the R_{sh} was 40 $\Omega/\square$ prior to post deposition alloying; after alloying in forming gas, R_{sh} of below 10 $\Omega/\square$ was achieved. Films deposited at 200 W were difficult to etch; hence an r.f. power of 150 W was used for all further work. Fig. 1 shows the results of ITO films deposited under various oxygen partial pressures at a r.f. power of 150 W. It is evident that the sheet resistance is directly proportional to the exponential of the oxygen partial pressure. Whereas the transparencies of these films were above 90% in the 500 nm to 2000 nm wavelength range, further reductions in the oxygen content severely degraded the transparency to below 60%.

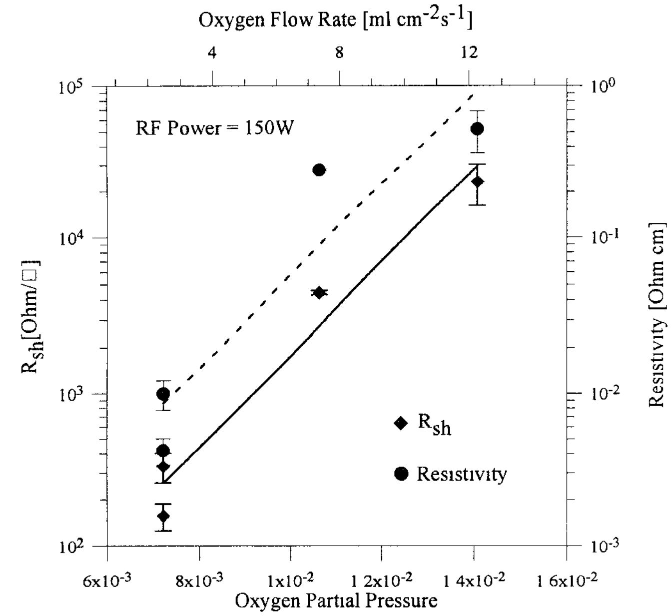

Fig. 1. Measured sheet resistance and resistivity of ITO films as a function of oxygen partial pressures in the Ar/O2 plasma during deposition; these were all carried out for 60 minutes at an RF power of 150 W.

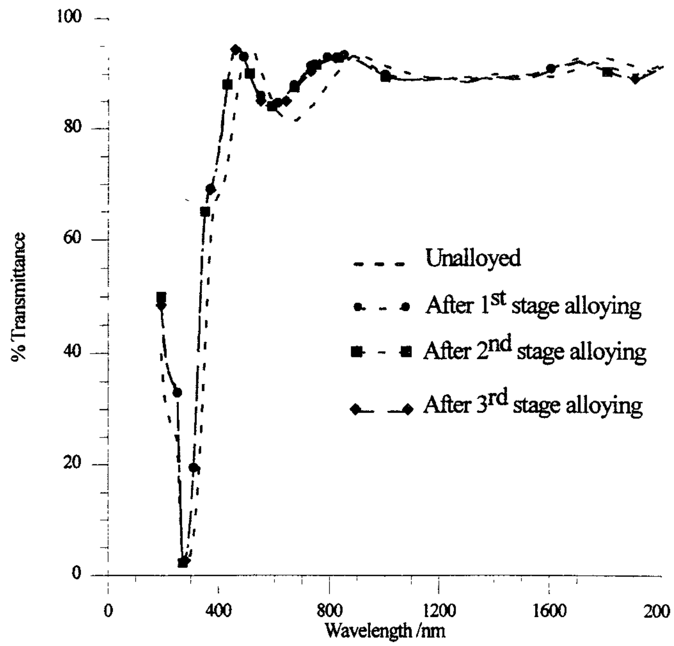

Fig. 2. Measured transmittance of ITO as deposited and as a function of thermal alloying stages.

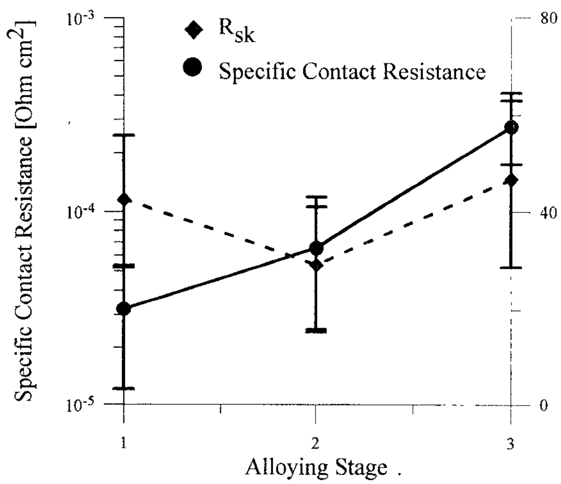

Fig. 3. Ohmic contact parameters of ITO to n^+ GaAs as a function of alloying.

B. ITO Definition and Ohmic Contacts

Due to the lack of control of wet chemical etching of ITO necessary for producing near micron structures, we have successfully used selective dry etching techniques with aluminum as the mask. Although CH_4/H_2 mixtures can be used for reactive ion etching of ITO layers, this is a potentially explosive gas mixture which requires relatively expensive exhaust set-ups. We have investigated the suitability of freon, oxygen & argon for dry etching ITO and found the latter to the most useful candidate. 100 W, at a pressure of 11 mTorr was decided to be the most controllable and suitable r.f. power and was used for all subsequent ITO dry etching work. The etch rates for ITO and Al were 35 Å/min and 7.8 Å/min respectively.

Fig. 2 shows the transmittance of ITO films deposited on microscope slides. Transmittance of greater than 90% has been achieved in the 500 nm to 2000 nm wavelength range. Fig. 3 shows the corresponding ohmic properties (specific contact resistance, $\rho_c = 3.2 \times 10^{-5}$ Ω cm^2, sheet resistance under the contact, $R_{sk} = 20$ $\Omega/\square$) of ITO contacts to n^+-GaAs layers grown on S.I. GaAs substrates as a function of alloying stages. The alloying was carried out in a forming gas ambient and the maximum temperature applied at each stage was 500°C. These results demonstrate that there is a minimal change in transmittance of the ITO film following the first stage of alloying and no noticeable change thereafter. Prior to alloying, the contacts showed rectifying behavior and were not measurable using the TLM method [10]. The R_{sk}, which is comparable to conventional opaque ohmic contacts also shows a minima after the first stage of alloying. Hence only one alloying stage was used during the fabrication of the HPT's. Although the cap layers in the InP/InGaAs HPT's consisted of n^+-InGaAs material, the same alloying scheme for the above ITO contacts (ITO on n^+-GaAs cap layers corresponding to GaAs/AlGaAs HPT's) was used and found to be successful.

C. Device Fabrication

A set of InP/InGaAs HBT devices were fabricated using standard photolithographic and wet chemical mesa etching steps. The epitaxial layers were grown at Epitaxial Products International of Cardiff, UK; in these structures, the base was typically doped to 5×10^{18} cm^{-3} with Zn dopants. Layer structure of the sample is shown in Fig. 4. ITO was deposited onto the n^+-InGaAs cap layer by reactive r.f. sputtering followed by dry etching for emitter contact definition. These were then annealed to obtain good ITO/n^+-InGaAs ohmic contacts. Au/Zn/Au and Ni/AuGe/Ni/Au metallization systems were used to make contacts to the base and collector layers respectively. No further alloying was carried out on these

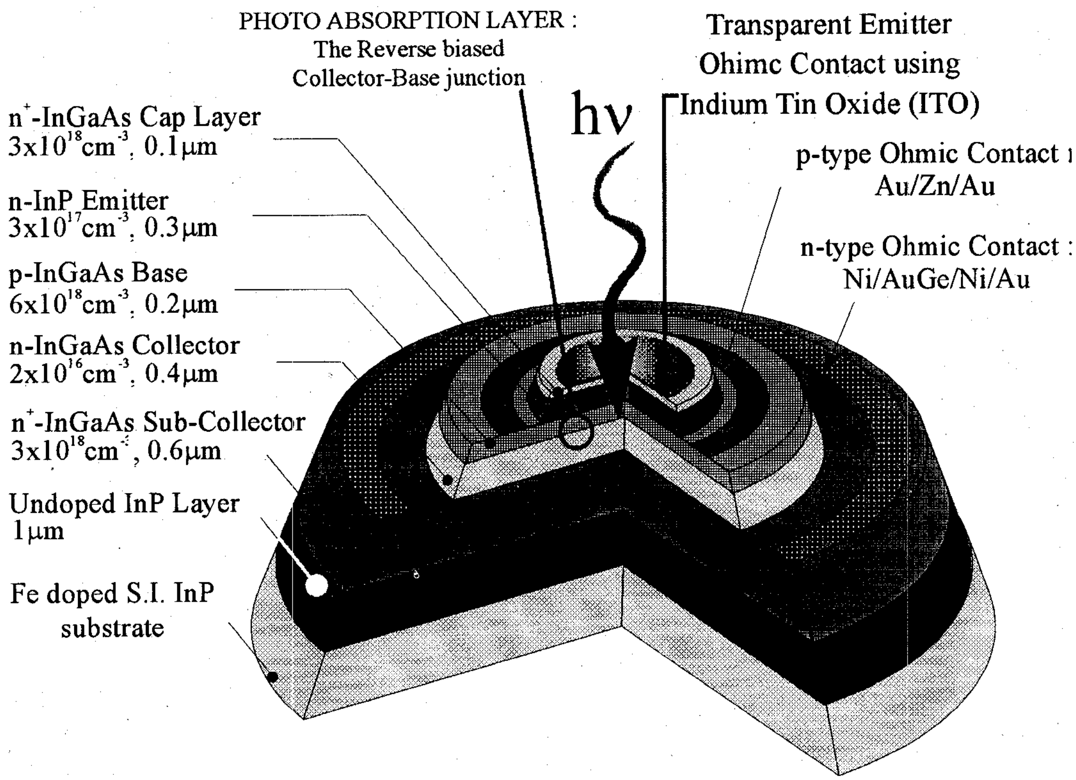

Fig. 4. Schematic device structure of an InP/InGaAs HPT with transparent ITO emitter ohmic contact.

devices. The emitter/base and base/collector areas were 8×10^{-5} cm^2 and 3.7×10^{-4} cm^2 respectively.

Individual devices were packaged on T05 headers and all DC measurements were carried out using a HP4145B semiconductor parameter analyzer (SPA). Responsivity measurements were performed by mounting the headers on an optical bench and using a 780-nm variable power solid state laser in conjunction with the SPA. The electrical base current input from the SPA was zero during the optical measurements, and the output collector current was recorded at various incident optical power levels. Spectral response measurements were carried out using a Bentham monochromator over the 450–1830-nm wavelength range.

III. Results and Discussion

Fig. 5 shows both the electrical and optical I-V characteristics of an InP/InGaAs HPT. The optical characteristics were generated by illuminating the device with light from a 780-nm variable power solid state laser. From Fig. 5 it is seen that at a constant illumination, the collector current is constant with the applied voltage indicating that there is no base width modulation or avalanche multiplication in the base/collector region.

Fig. 5 also shows that the HPT can be controlled both optically and electrically or by a combination of both sources. This represents the potential to use of a single device for the simultaneous detection and amplification of an optical signal as well as its subsequent coupling with an electrical signal in a single device.

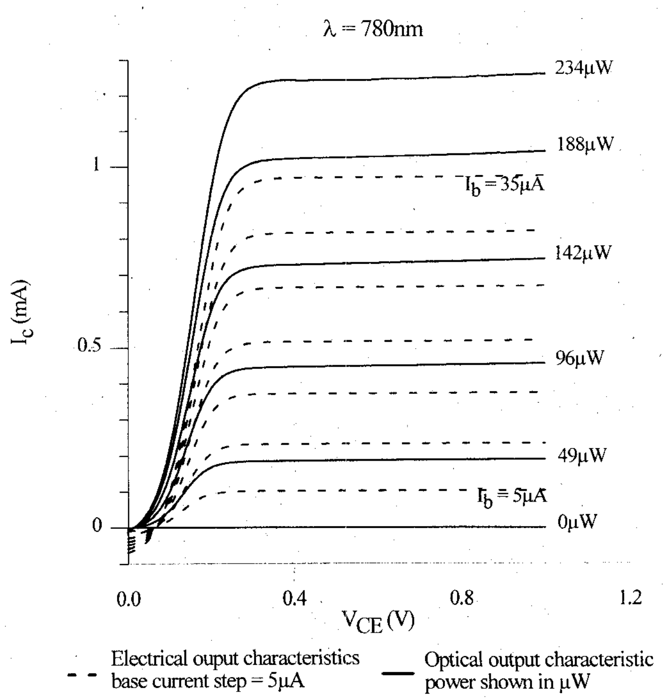

Fig. 5. Measured common-emitter electrical and optical characteristics of an optically transparent emitter contact InP/InGaAs heterojunction phototransistor (HPT) fabricated using ITO (λ = 780 nm).

The room temperature Gummel plot for a typical ITO emitter contact HPT is shown in Fig. 6. One obvious feature of this data is that the linear part of I_c, where thermionic emission is dominant, occupies more than seven decades in current. Furthermore, the turn-on voltage of the device is very

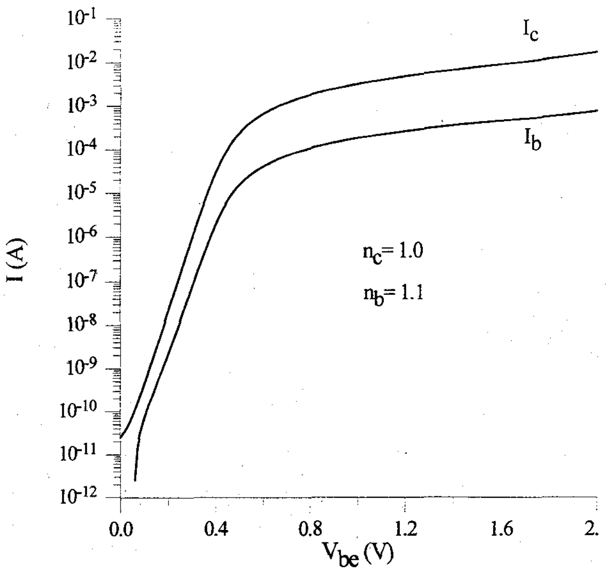

Fig. 6. Gummel plot measured in the dark for the optically transparent ITO emitter contact HPT.

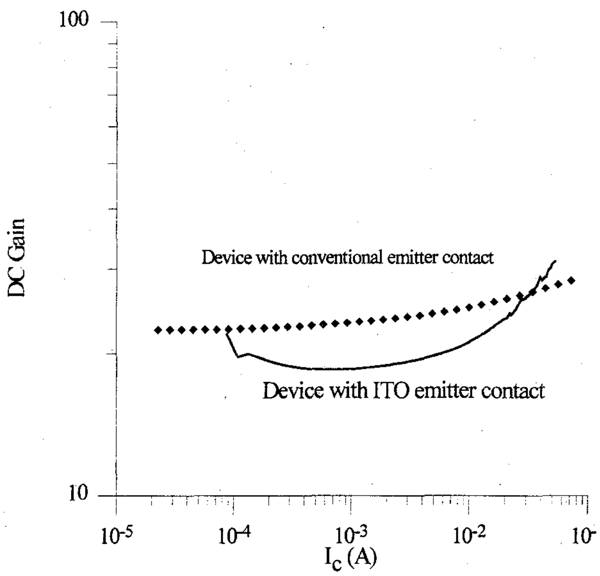

Fig. 7. Measured current gains versus collector current for InP/InGaAs HBT devices with an opaque and a ITO emitter contact ($V_{CE} = 2$ V).

low (≤ 0.1 V) indicating the suitability of these devices for low power circuit applications. The ideality factor for the collector current is $n_c = 1.0$ and for the base current $n_b = 1.1$ which is indicative of a high quality emitter base interface.

A comparison of the current gain vs. the collector current between an opaque emitter and an optically transparent emitter contact HPT is made and this is shown in Fig. 7. The ITO devices shows a reduction in current gain most likely due to higher emitter series resistance (arising from a higher resistance asscociated with the ITO contact) compared to its opaque counterpart.

Fig. 8 shows the normalized deconvoluted spectral response of ITO emitter contact InP/InGaAs HPT. The measured spectral response is divided by the blackbody radiancy (from the tungsten filament lamp in the monochromator) corresponding

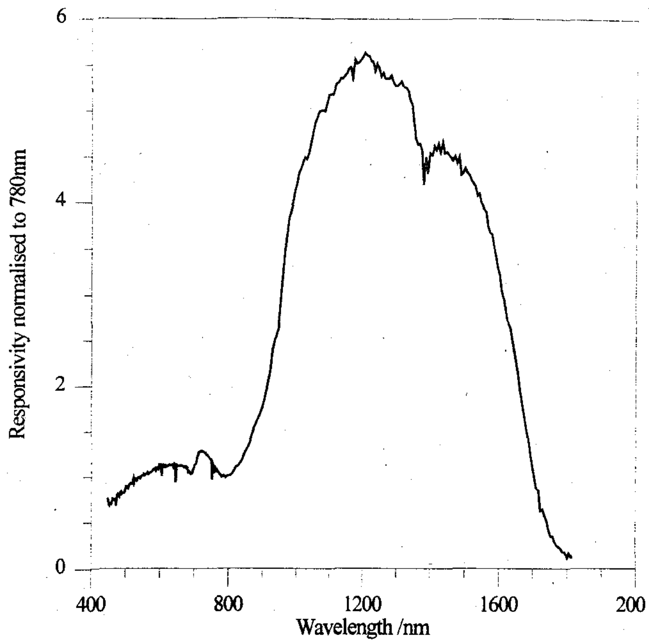

Fig. 8. Deconvoluted spectral response, normalized to 780 nm, of InP/InGaAs HPT with ITO emitter contacts at 300 K ($V_{CE} = 1$ V).

to each wavelength or is 'deconvoluted' to observe the actual device characteristics at various wavelengths. The long wavelength cut-off is determined by the absorption edge of the narrow-bandgap base and collector. For $In_{0.53}Ga_{0.47}As$ this corresponds to a wavelength of approximately 1.65 μm. At shorter wavelengths (<0.95 μm), the photoresponse is limited by absorption in the InP emitter. The dip in the spectral response at around 1400 nm corresponds to atmospheric absorption of radiation from the monochromator and is not a reflection of the device characteristic.

The suitability of the InP/InGaAs devices for operation at 1310- and 1550-nm wavelengths is clearly demonstrated in Fig. 8. Device responsivities of up to 30 A/W and 22 A/W at 1310 and 1550-nm wavelengths respectively are suggested by the normalized spectral response. Although greater absolute responsivities have been reported for opaque InP/InGaAs HPT devices [2],[3], our low values can be attributed to the relatively low internal DC current gains of the devices rather than the external optical coupling efficiency.

Further work is currently in progress to fabricate small geometry devices using ITO emitter contacts for microwave and integrated optoelectronic applications.

IV. Conclusion

Details of the fabrication of transparent indium tin oxide (ITO) emitter contacts to InP/InGaAs HPT's have been reported for the first time and the results compared with those of opaque emitter contacts having similar device layout and fabrication steps. We have also reported the optimization of ITO deposition conditions (RF power = 150 W, oxygen partial pressure = 7.3×10^{-3}) and demonstrated selective dry etching of this material using nonhazardous Ar plasma suitable for small geometry pattern definition.

The successful fabrication of InP/InGaAs heterojunction phototransistors using transparent ITO ohmic contacts to the emitter has been shown. These devices exhibit comparable electrical characteristics and enhanced optical coupling to their opaque counterparts. With further optimization and development, the optically transparent emitter HPT should be very useful as a detector for high efficiency optoelectronic mixer, as well as in mobile and long haul optical telecommunication system applications.

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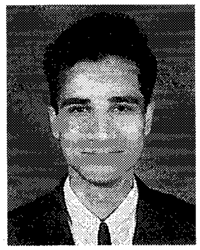

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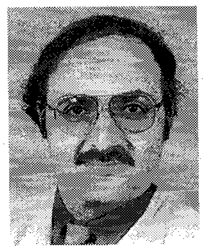

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