An $In_{0.52}Al_{0.48}As/n^+$-$In_{0.53}Ga_{0.47}As$ MISFET with a Heavily Doped Channel

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***Abstract*—An $In_{0.52}Al_{0.48}As/n^+$-$In_{0.53}Ga_{0.47}As$ MIS-type field-effect transistor (FET) with a channel doped at a 7×10^{17} cm^{-3} level has been fabricated on an InP substrate. A device with a 2-μm channel length has yielded a maximum transconductance of 152 mS/mm, f_T = 12.4 GHz, and f_{max} = 50 GHz. At 10 GHz, the maximum available gain is 17.4 dB. The performance of this device shows that heavily doped channel FET's are very promising for high-frequency operation.**

THE ternary alloy $In_{0.53}Ga_{0.47}As$ has recently attracted alot of interest for field-effect transistor (FET) applications to long-wavelength optoelectronics based on InP substrates. Among its merits, a high room-temperature electron mobility, a high electron peak velocity, and a large conduction band Γ-*L* valley separation [1] provide $In_{0.53}Ga_{0.47}As$ with unique qualifications for high-speed and high-frequency operation.

The low barrier height of metals on n-$In_{0.53}Ga_{0.47}As$ prevents the fabrication of conventional metal-semiconductor FET's (MESFET's). To overcome this problem, $In_{0.52}Al_{0.48}As$ has been utilized as a gate insulator [2] because it is lattice matched to $In_{0.53}Ga_{0.47}As$ and offers substantial conduction-band discontinuity, about 0.5 eV [3].

Improved performance has been demonstrated in GaAs MESFET's when the channel region is thin and heavily doped [4], [5]. Particularly in the submicrometer regime, reduced short-channel effects have been demonstrated [5]. This possibility has yet to be exploited in $In_{0.52}Al_{0.48}As$/n-$In_{0.53}Ga_{0.47}As$ devices where the typical channel doping concentration reported to date is in the 1-2 $\times 10^{17}$ cm^{-3} range and thickness is in the 1000-1500-Å range [2], [6], [7]. In this letter we report $In_{0.52}Al_{0.48}As/n^+$-$In_{0.53}Ga_{0.47}As$ FET's with channels one order of magnitude thinner and several times more heavily doped than anything fabricated to date in this semiconductor system. The potential of this approach for high-frequency applications is demonstrated.

The device structure is shown in Fig. 1. It was grown by molecular beam epitaxy (MBE) on a semi-insulating (100) Fe:InP substrate at 520°C. A 1000-Å $In_{0.52}Al_{0.48}As$ buffer layer was followed by a 300-Å $In_{0.53}Ga_{0.47}As$ "smoothing layer" and the 200-Å-thick $In_{0.53}Ga_{0.47}As$ active channel was doped with Si to a level of 7×10^{17} cm^{-3} (value obtained from *C-V* measurements). The gate insulator consisted of 300 Å of $In_{0.52}Al_{0.48}As$ followed by a 50-Å $In_{0.53}Ga_{0.47}As$ cap layer. All layers, except for the active channel, are nominally undoped. The lattice mismatch among the grown layers and the InP substrate is smaller than 0.1 percent.

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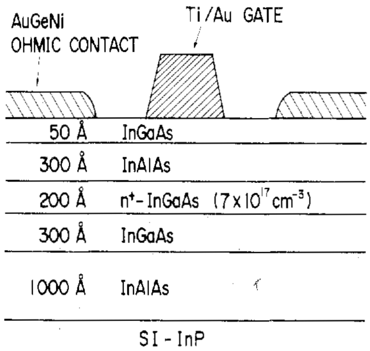

Fig. 1. Schematical cross section of device structure.

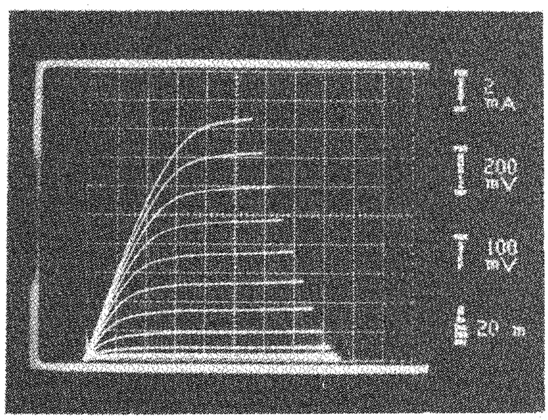

Fig. 2. Current-voltage characteristics of a 2 × 200-μm^2 gate device at room temperature. The maximum gate-source voltage is 0.4 V.

A mesa structure provided the required isolation. Ohmic contacts were performed by alloying evaporated AuGeNi at 370°C for 30 s. The gate and interconnect layers were fabricated simultaneously by lifting off evaporated Ti/Au. The shortest gate length that was obtained was 2 μm (measured by scanning electron microscope).

Fig. 2 shows typical room-temperature *I-V* characteristics of a 2 × 200-μm^2 device with double gate feeder. Fig. 3 shows the transconductance and square root of the drain current of the same device as a function of gate-source voltage, for a drain-source voltage of 3.5 V. A maximum transconductance of 152 mS/mm, a *K* value of 139 mS/V·mm, and a threshold voltage of −0.65 V were deduced. The drain-source breakdown voltage was around 7 V (hard breakdown) and the gate-source breakdown voltage was about 5 V (soft breakdown, I_{GS} = 20 mA).

The transconductance as a function of gate-source voltage displays a broad plateau beyond its peak. This is in contrast to

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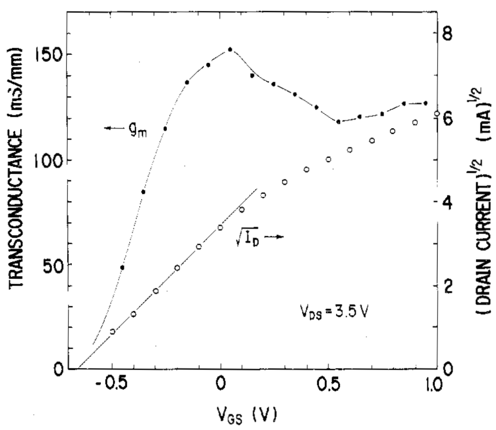

Fig. 3. Transconductance and square root of drain current versus gate-source voltage for the device of Fig. 2 at room temperature.

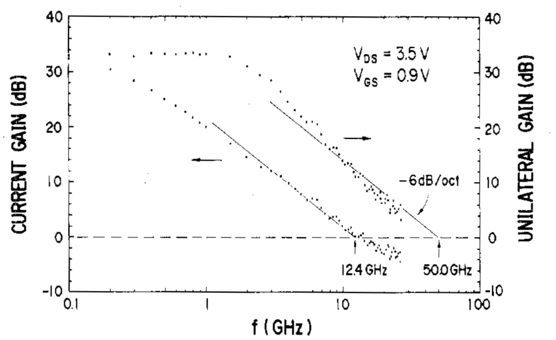

Fig. 4. Current gain and unilateral gain of 2 × 200-μm^2 FET versus frequency.

$In_{0.52}Al_{0.48}As/In_{0.53}Ga_{0.47}As$ modulation-doped FET's (MODFET's) [8] which show a sharp peak in transconductance due to the onset of parallel conduction in the selectively doped $In_{0.52}Al_{0.48}As$ layer at high gate–source biases. MESFET's suffer from a similar problem due to the increased gate current that results from the almost complete disappearance of the gate barrier under large gate–source bias. On the other hand, in the device presented here, the 0.5-eV conduction-band discontinuity between channel and gate insulator confines the electrons to the channel and strong gate–source forward bias can be applied. The high transconductance at high gate–source voltages constitutes a significant merit of this metal/insulator/doped-channel structure over MODFET's and MESFET's for large input signals. A similar result to ours was recently obtained in AlGaAs/n^+-GaAs FET's [9].

In an adjoining transmission-line pattern, a contact resistance of 0.77 Ω·mm and a sheet resistance of 600 Ω/sq were measured. Since the source–gate separation of the FET is 0.8 μm, its total source resistance is 1.25 Ω·mm. The presently high contact resistance is not likely to limit the performance of this device in the future since values as small as 0.06 Ω·mm have been reported in similar $In_{0.52}Al_{0.48}As/n^+\text{-}In_{0.53}Ga_{0.47}As$ structures [10].

Fig. 4 shows the current gain and unilateral gain versus frequency obtained from microwave S-parameter measurements at a drain–source voltage of 3.5 V and a gate–source voltage of 0.9 V. Neither the unilateral gain nor the current gain follow a −6-dB/octave decay at high frequencies. With the precise origin still unknown, this effect may be due to the presence of intrinsic or extrinsic parasitic elements outside those of the common equivalent circuit [11]. The extraction of f_T and f_{max} using the conventional extrapolation technique cannot be applied in this case. We have estimated these cutoff frequencies by taking an average of the intersections with the zero gain axis of −6-dB/octave slope lines taken from all data points above 3 GHz. The resulting figures are f_T = 12.4 GHz and f_{max} = 50 GHz. Straight extrapolation of the data yields otherwise f_T = 14 GHz and f_{max} = 35 GHz, although some authors do not believe this simple technique to be correct [12]. The f_T = 12.4-GHz figure essentially coincides with an extrapolation of the values reported in state-of-the-art $In_{0.52}Al_{0.48}As/In_{0.53}Ga_{0.47}As$ MODFET's [8], [13]–[16] to our 2-μm gate length.

A more accurate relative assessment of the microwave performance of the present device with respect to other devices can be obtained by comparing their maximum available gain (MAG) at a given frequency, for example, 10 GHz. At 10 GHz, our device is unconditionally stable ($K > 1$) and has a MAG of 17.4 dB. This value is higher than that of 1-μm gate-length $Al_{0.25}Ga_{0.85}As/GaAs$ [17], $Al_{0.15}Ga_{0.85}As/In_{0.15}Ga_{0.85}As$ [13], [17], and $In_{0.52}Al_{0.48}As/In_{0.53}Ga_{0.47}As$ [13] MODFET's, which have yielded 11, 13, and 16.3 dB, respectively.

In conclusion, an $In_{0.52}Al_{0.48}As/n^+\text{-}In_{0.53}Ga_{0.47}As$ MISFET has been fabricated by MBE. At a gate length of 2 μm, a maximum transconductance of 152 mS/mm, f_T = 12.4 GHz, and f_{max} = 50 GHz have been measured. These values demonstrate the performance potential of this device when scaled to submicrometer dimensions.

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