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

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Abstract—**A heterostructure metal-insulator-semiconductor field-effect transistor (MISFET) with a modulation-doped channel is proposed. In this device, a very thin undoped subchannel is located between the undoped wide-bandgap insulator and a thin heavily doped channel. In the depletion mode of operation, electron transport takes place along the heavily doped channel. When the device enters the accumulation mode of operation, electrons pile up against the heterointerface in the high-mobility undoped subchannel. This should result in markedly improved transport characteristics at the onset of accumulation. The concept is demonstrated in the $In_{0.52}Al_{0.48}As/In_{0.53}Ga_{0.47}As$ system on InP. A 1.5-μm gate length MISFET has shown a unity current-gain cutoff frequency of 37 GHz.**

THE OUTSTANDING electron transport properties of $In_{0.53}Ga_{0.47}As$ have recently attracted a lot of interest in the pursuit of high-performance field-effect transistors on InP substrates, the keystone of long-wavelength optoelectronics [1]. A number of FET device structures have been demonstrated. While excellent performance has recently been obtained in $In_{0.52}Al_{0.48}As/In_{0.53}Ga_{0.47}As$ modulation-doped field-effect transistors (MODFET's) of submicrometer dimensions [2], $In_{0.52}Al_{0.48}As/In_{0.53}Ga_{0.47}As$ metal–insulator–semiconductor field-effect transistors (MISFET's) have also been found to be very promising [3]. The fundamental difference between both types of devices is the presence of dopant atoms inside the wide-bandgap gate insulator in the case of a MODFET and its absence in a MISFET. Because of this, a MISFET does not suffer either from DX centers, or transconductance collapse due to the formation of a parallel conduction channel inside the gate semiconductor, as is known to occur in MODFET's. A MISFET also enjoys more flexible scaling of the insulator thickness and a higher breakdown voltage than a MODFET.

MISFET's with a thin heavily doped channel have also been recently demonstrated in the $In_{0.52}Al_{0.48}As/In_{0.53}Ga_{0.47}As$ system by the present and other authors [4]–[8]. In spite of the high doping of the channel, microwave performance comparable with MODFET's of the same gate dimensions was realized. Further improved characteristics could be obtained if the mobility was not limited by ionized impurity scattering inside the highly doped channel. To overcome this severe limitation, in this work we propose and demonstrate a *modulation-doped channel MISFET.*

In order to understand the key concept underlying the modulation-doped channel MISFET, the two main modes of operation of a doped-channel MISFET must be briefly reviewed [5]. In the *depletion mode* of operation, the channel is partially depleted of electrons and conduction between source and drain takes place along the deeper undepleted portion of the channel. If sufficient forward gate–source voltage is applied, the depletion region can be completely eliminated and accumulation of electrons takes place adjacent to the heterointerface. This is the *accumulation mode* of operation.

In the modulation-doped channel MISFET, a thin undoped subchannel is placed between the insulator and the doped channel. When the device enters the accumulation regime, electrons pile up precisely at the undoped subchannel close to the heterointerface where they exhibit a significantly higher mobility. A marked improvement in performance is to be expected at the onset of accumulation. In this paper we demonstrate this concept in the $In_{0.52}Al_{0.48}As/In_{0.53}Ga_{0.47}As$ system.

A cross section of the device structure is shown in Fig. 1. It was grown by molecular-beam epitaxy on a semi-insulating (100) Fe:InP substrate at a substrate temperature of 520°C and a group V-to-III flux ratio of 20. The lattice mismatch between the grown layers and the substrate is better than 0.1 percent. From bottom to top, the following layers were grown: a 1000-Å $In_{0.52}Al_{0.48}As$ buffer layer, a 300-Å $In_{0.53}Ga_{0.47}As$ smoothing layer, a 120-Å Si-doped (1.5×10^{18} cm^{-3}) $In_{0.53}Ga_{0.47}As$ subchannel, a 50-Å undoped $In_{0.53}Ga_{0.47}As$ subchannel, a 300-Å $In_{0.52}Al_{0.48}As$ insulator, and a 50-Å $In_{0.53}Ga_{0.47}As$ cap layer. All layers except the heavily doped subchannel are undoped. After MBE growth, device processing proceeded with mesa isolation down to the InP substrate performed by means of a selective chemical etchant (H_2SO_4:H_2O_2:H_2O, 1:10:100). AuGeNi alloyed ohmic contacts were e-beam evaporated, lifted off, and alloyed at 400°C for 30 s. A Ti/Au gate and Ti/Au contact pads were also formed by e-beam evaporation and lift off.

As a reference, a doped-channel MISFET without the 50-Å undoped subchannel but otherwise with an identical layer structure was grown immediately after the modulation-doped channel MISFET described above. In this device, therefore, electron accumulation takes place in the heavily doped channel. Device processing was carried out simultaneously with the modulation-doped channel MISFET.

Fig. 2 shows the *I–V* characteristics of a typical 1.5×200-μm^2 gate modulation-doped channel MISFET. The maximum

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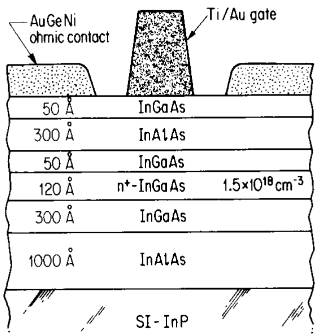

Fig. 1. Schematical cross section of fabricated modulation-doped channel MISFET.

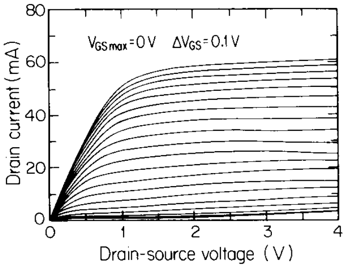

Fig. 2. I-V characteristics of 1.5×200-μm^2 gate modulation-doped channel MISFET.

transconductance of this device is 206 mS/mm. The best transconductance that we have observed in a device of these gate dimensions is 225 mS/mm. For comparison, the best 1.5-μm gate length reference MISFET showed only a transconductance of 164 mS/mm. The maximum drain current obtained from the device shown in Fig. 2 is higher than 300 mA/mm. The contact resistance and the extrinsic source sheet resistance are, respectively, 0.16 Ω·mm and 430 Ω/□. Since the source-gate separation is 1 μm, the source resistance is about 0.59 Ω·mm. For comparison, the figures of merit in the reference MISFET are, respectively, 225 mA/mm, 0.74 Ω·mm, 570 Ω/□, and 1.31 Ω·mm.

We have carried out microwave S-parameter measurements from 100 MHz to 26.5 GHz and extracted the current gain h_{21}. Fig. 3 plots h_{21} as a function of frequency for a modulation-doped channel MISFET and a reference MISFET with 1.5×200-μm^2 gates. The bias voltages have been optimized to obtain the highest possible current gain in each device. In both devices, the current gain decays with frequency with a slope of −6 dB/octave. The current-gain cutoff frequency f_T for the reference MISFET is 15.2 GHz. This value is consistent with our previous result of 12.4 GHz in a 2.0-μm FET [4]. In contrast, f_T for the modulation-doped channel MISFET is 37 GHz, more than a factor of 2 improvement over the reference MISFET with the same gate length. The MSG of the modulation-doped channel MISFET is 14.7 dB at 26.5 GHz ($K = 0.58$).

Gate leakage is very small. For example, at the bias point at peak f_T in the modulation-doped channel MISFET, $I_G = 0.25$ mA. Gate breakdown is soft. A current of 3.7 mA flows at $V_{GS} = -2$ V.

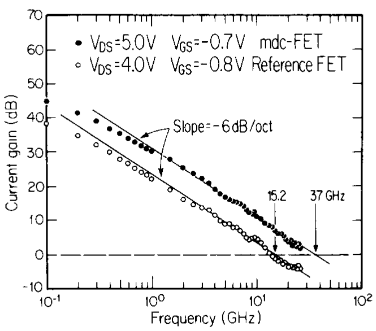

Fig. 3. Current gain as a function of frequency for modulation-doped channel MISFET and reference MISFET of 1.5×200-μm^2 gate dimensions.

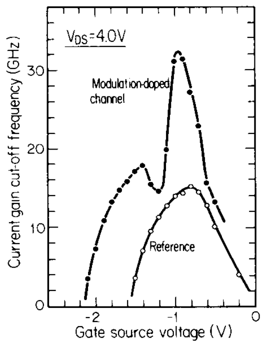

Fig. 4. f_T as a function of gate-source bias for modulation-doped channel MISFET and reference MISFET of 1.5×200-μm^2 dimensions.

Of foremost interest is the analysis of the gate bias V_{gs} dependence of f_T for both types of devices. Fig. 4 displays the result of such measurements. f_T in the reference MISFET increases beyond threshold, peaks at 15.2 GHz, and then decreases. The reduction of f_T at high gate bias observed in this device contrasts strongly with earlier measurements of f_T versus V_{gs} in our first MISFET implementation in which we found f_T to be rather insensitive to V_{gs} over a range of more than 1 V [5]. It is possible, therefore, that the drop observed in the present device is not intrinsic to the device structure but is due to the existence of traps inside the $In_{0.52}Al_{0.48}As$, as will be discussed below.

f_T in the modulation-doped channel MISFET increases over threshold following a bias dependence identical to the reference MISFET. This is the expected behavior, since both devices initially operate in the depletion regime. Beyond a small dip, f_T increases sharply at about $V_{gs} = -1.1$ V. In this particular device (different from the best one with $f_T = 37$ GHz, reported above), f_T reaches a maximum value of 31.4 GHz, more than two times the reference MISFET. Beyond this peak, f_T decreases in much the same way as the reference device does.

The sudden increase of f_T at −1.1 V in the modulation-doped channel MISFET reflects the onset of a new mode of operation that we attribute to the accumulation regime in which electrons pile up at the undoped $In_{0.53}Ga_{0.47}As$ layer closest to the heterointerface. The mobility of electrons in undoped $In_{0.53}Ga_{0.47}As$ can be as high as 2.5 times the corresponding value for $In_{0.53}Ga_{0.47}As$ doped to the 10^{18} cm^{-3} level [9]. Such an increase in mobility in our relatively long devices can explain the sudden increase of f_T that we observe in the modulation-doped channel MISFET at -1.1 V and its difference with the best f_T exhibited by the reference doped-channel MISFET.

In a doped-channel MISFET, simple theory indicates that the accumulation regime takes place when the gate voltage is higher than the flat-band voltage V_{FB} [5]. This was, in fact, experimentally observed in our first implementation of $In_{0.52}Al_{0.48}As/n^+$-$In_{0.53}Ga_{0.47}As$ MISFET's [4], [5]. For the present device structure, $V_{FB} \simeq 0.3$ V. However, the sharp increase in f_T, shown in Fig. 4, takes place at about -1.1 V. A shift of V_{FB} of about -1.4 V is required to reconcile theory and experiments. Such a shift in V_{FB} may result from the presence of traps inside the $In_{0.52}Al_{0.48}As$ insulator. Reports on the observation of traps in undoped MBE-grown $In_{0.52}Al_{0.48}As$ have been recently published [10]-[14].

By measuring the C-V characteristics of an adjoining 200-μm-diameter diode at 77 K, we have independently confirmed that the peak in f_T does actually take place when the device enters accumulation. The C-V characteristics showed some frequency dispersion and hysteresis, a behavior expected when traps exist in the insulator. The capacitance in the accumulation regime was about 94 pF, in excellent agreement with the expected theoretical value of 97 pF based on the diode geometry.

The presence of traps, therefore, shifts the flat-band voltage towards negative values by about 1.4 V. Consistent with this shift, we have also observed a deviation of threshold voltage of about -1.1 V from the theoretically expected value. Other than these voltage shifts, the traps should not affect the basic operations of the device. Indeed, a prominent enhancement of f_T is observed precisely at the same voltage at which the C-V measurements indicate the onset of accumulation, demonstrating the modulation-doped channel concept.

Detailed analysis of the y parameters extracted from microwave S-parameter measurements revealed that the prominent peak in f_T of Fig. 4 was due to a sudden increase in transconductance. Such an increase is not observed in the dc output characteristics of Fig. 2. In fact, while the maximum g_m obtained in dc measurements is 206 mS/mm for the device shown in Fig. 2, g_m obtained from Re[y_{21}] is 380 mS/mm. We have observed this systematic discrepancy between g_m (dc) and g_m (HF) in all our InAlAs/n^+-InGaAs MISFET's including the reference MISFET described in this paper. Similar observations have been recently reported by Kuang *et al.* on similar submicrometer InAlAs/n^+-InGaAs MISFET's [8]. The origin of this effect is unclear at present, but the presence of trap states at the InAlAs/InGaAs interface could account for it [15].

In summary, a MISFET with a modulation-doped channel has been proposed and demonstrated in the $In_{0.52}Al_{0.48}As/In_{0.53}Ga_{0.47}As$ system. The device displays a sudden increase in its current-gain cutoff frequency that we attribute to the onset of the accumulation mode of operation in which electrons pile up inside a very thin undoped $In_{0.53}Ga_{0.47}As$ layer adjoining the heterointerface.

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REFERENCES

[1] A. Suzuki, K. Kasahara, and M. Shikada, "InGaAsP/InP long wavelength optoelectronic integrated circuits (OEIC's) for high-speed optical fiber communication systems," *IEEE J. Lightwave Technol.* vol. LT-5, no. 10, pp. 1479-1487, 1987.

[2] U. K. Mishra *et al.*, "Microwave performance of AlInAs-GaInAs HEMT's with 0.2- and 0.1-μm gate length," *IEEE Electron Device Lett.*, vol. 9, no. 12, pp. 647-649, 1988.

[3] M. D. Feuer, J. M. Kuo, S. C. Shunk, R. E. Behringer, and T.-Y. Chang, "Microwave performance of InGaAs/InAlAs/InP SISFET's," *IEEE Electron Device Lett.*, vol. 9, no. 4, pp. 162-164, 1988.

[4] J. del Alamo and T. Mizutani, "An $In_{0.52}Al_{0.48}As/n^+$-$In_{0.53}Ga_{0.47}As$ MISFET with a heavily doped channel," *IEEE Electron Device Lett.*, vol. EDL-8, no. 11, pp. 534-536, 1987.

[5] J. del Alamo and T. Mizutani, "Bias dependence of f_T and f_{max} in an $In_{0.52}Al_{0.48}As/n^+$-$In_{0.53}Ga_{0.47}As$ MISFET," *IEEE Electron Device Lett.*, vol. 9, no. 12, pp. 654-656, 1988.

[6] A. Fathimulla, H. Hier, and J. Abrahams, "Microwave performance of pulse-doped-heterostructure GaInAs MESFET's," *Electron. Lett.*, vol. 24, no. 2, pp. 93-94, 1988.

[7] A Fathimulla, H. Hier, and J. Abrahams, "High-current pulse-doped GaInAs MESFET's," *Electron. Lett.*, vol. 24, no. 8, pp. 498-499, 1988.

[8] J. B. Kuang *et al.*, "Submicron-gate $In_{0.52}Al_{0.48}As/In_{0.53}Ga_{0.47}As/In_{0.52}Al_{0.48}As$ heterojunction metal-semiconductor field-effect transistors grown by molecular beam epitaxy," *Appl. Phys. Lett.*, vol. 54, no. 12, pp. 1136-1138, 1989.

[9] T. P. Pearsall *et al.*, "Electron and hole mobilities in $Ga_{0.47}In_{0.53}As$," *Inst. Phys. Conf. Ser.*, vol. 56, pp. 639-649, 1981.

[10] G. J. Davies and D. A. Andrews, "The effect of As_4 overpressure on the incorporation of In into $Al_{1-x}In_xAs$ grown on (100) InP by molecular beam epitaxy," *J. Phys. D.*, vol. 17, pp. L143-L146, 1984.

[11] P. S. Whitney, S. Lee, and C. G. Fonstad, "Capacitance transient analysis of molecular-beam epitaxial n-$In_{0.53}Ga_{0.47}As$ and n-$In_{0.52}Al_{0.48}As$," *J. Vac. Sci. Technol.*, vol. B5, no. 3, pp. 796-799, 1987.

[12] K. Nakashima, S. Nojima, Y. Kawamura, and H. Asahi, "Deep electron trapping centers in Si-doped InAlAs grown by molecular beam epitaxy," *Phys. Stat. Sol.* (a), vol. 103, pp. 511-516, 1987.

[13] S. Nojima, K. Nakashima, Y. Kawamura, and H. Asahi, "Effects of deep levels on the optoelectronic properties of InGaAs/InAlAs multiquantum-well structures," *J. Appl. Phys.*, vol. 63, no. 6, pp. 1955-1960, 1988.

[14] J. B. Kuang *et al.*, "Kink effect in submicrometer-gate MBE-grown InAlAs/InGaAs/InAlAs heterojunction MESFET's," *IEEE Electron Device Lett.*, vol. 9, no. 12, pp. 630-632, 1988.

[15] T. Sugano, F. Koshiga, K. Yamasaki, and S. Takahashi, "Application of anodization in oxygen plasma to fabrication of GaAs IGFET's," *IEEE Trans. Electron Devices*, vol. ED-27, no. 2, pp. 449-455, 1980.