Characterization of ion-implanted $In_xGa_{1-x}As/GaAs$ 0.25 μm gate metal semiconductor field-effect transistors with $F_t > 100$ GHz

M. Feng, J. Laskar, W. Miller, J. Kolodzey, and G. E. Stillman
Center for Compound Semiconductor Microelectronics, Department of Electrical and Computer Engineering, University of Illinois at Urbana–Champaign, Urbana, Illinois 61801

C. L. Lau
Ford Microelectronics, Inc., 9965 Federal Drive, Colorado Springs, Colorado 80921

(Received 29 October 1990; accepted for publication 13 March 1991)

This work presents millimeter wave performance achieved by ion-implanted InGaAs/GaAs metal semiconductor field-effect transistor devices. A current gain cutoff frequency f_t of 126 GHz and maximum frequency of oscillation f_{max} of 232 GHz have been measured for 0.20 μm gate length devices. The f_t and low-field Hall mobility data, measured at 300 and 112 K, lead us to conclude that the average electron velocity under the gate is mainly due to the high-field velocity rather than low-field electron mobility.

InGaAs materials have been recognized for high-frequency and high-speed device applications due to the large energy separation between Γ and L valleys. Molecular beam epitaxy (MBE) grown $In_{0.08}Ga_{0.92}As/GaAs$ metal semiconductor field-effect transistors (MESFETs) with a 0.5 μm gate length have demonstrated excellent microwave performance with an f_t of 36 GHz and an f_{max} of 65 GHz.[1] Subsequently, ion-implanted MESFETs with a 0.5 μm gate length fabricated on $In_{0.1}Ga_{0.9}As/GaAs$ and $In_{0.18}Ga_{0.82}As/GaAs$ grown by metalorganic chemical vapor deposition (MOCVD) have achieved an f_t of 61 GHz.[2,3] This result is comparable to the highest f_t of 62 GHz achieved by InGaAs/GaAs pseudomorphic high electron mobility transistors (HEMTs) with 0.5 μm gate lengths.[4]

In this work, 0.25 μm gate length InGaAs MESFETs were fabricated by ion implantation into $In_xGa_{1-x}As$ grown by MOCVD on a GaAs substrate. Microwave performance was measured with an f_t of 126 GHz and f_{max} of 232 GHz. The f_t data and low-field Hall mobility data were also measured at 300 and at 112 K.

The InGaAs epitaxial layer is grown directly on 3 in. GaAs substrates by MOCVD techniques. The material structure consists of an undoped, 600 Å layer of $In_{0.18}Ga_{0.82}As$ followed by an undoped, 1000-Å-thick layer of $In_xGa_{1-x}As$ with the indium composition graded from $x = 0.18$ to $x = 0$ at the surface. The advantage for graded $In_xGa_{1-x}As$ layer is to improve the Schottky gate barrier height and, therefore, to reduce the gate leakage current.

The MESFET active channel is formed by ion-implanted Si + 29 ion species and subsequent capless annealing at 850 °C for 20 min. The surface morphology is smooth for the as-grown InGaAs layer, however, the implanted and annealed InGaAs layers show a few visible strained lines on the surface. From the capacitance voltage (C-V) measurement, the peak carrier concentration of 2×10^{18} cm^{-3} occurred at 0.08 μm. The carrier concentration of 1.8×10^{18} cm^{-3}, sheet resistance of 273 Ω/square, and mobility of 1068 cm^2/V s are obtained by Hall measurement. This mobility is 1/2 times lower compared to the epitaxial sample, which leads us to suggest either that implanted damage is not fully recovered or that the higher dislocations exist in the InGaAs buffer layer. Further study is needed to clarify these issues. The implant activation is 85%.

Electron beam direct write is used to define 0.25 μm T-shaped gates with widths of 200, 150, 100, and 50 μm. The recess etch depth is around 500 Å. Ti/Pt/Au gate metal is evaporated after recess etch. The drain-to-source spacing is 2.0 μm. The gate-to-source spacing is 0.25 μm to reduce the source resistance. Device isolation is achieved by mesa etching.

The drain current as a function of gate voltage for a 0.25×200 μm gate InGaAs MESFET is shown in Fig. 1. At $V_{gs} = 0$ V and $V_{ds} = 1.6$ V, this device shows an extrinsic transconductance of 428 mS/mm, the output conductance of 40 mS/mm at a current density of 420 mA/mm. The transconductance for a typical 0.25×50 μm gate InGaAs MESFET is 458 ± 21 mS/mm (average over 15 MESFETs) at $V_{gs} = 0$ V and $V_{ds} = 1.6$ V.

Microwave S parameters for 139 of 0.25×200 μm implanted devices across a 3 in. wafer are measured over the 0.5–25 GHz frequency range at $V_{gs} = 0$ V and $V_{ds} = 1.6$ V using an HP8510 automatic network analyzer with Cascade Microtech microwave probes. The f_t is obtained by extrapolating $|H_{21}|$ to unity gain with a -6 dB/octave

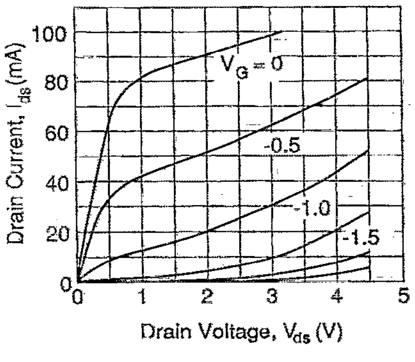

FIG. 1. Drain current (I_{ds}) and drain voltage (V_{ds}) as a function of gate voltage for a typical 0.25×200 μm gate, implanted InGaAs/GaAs MESFET.

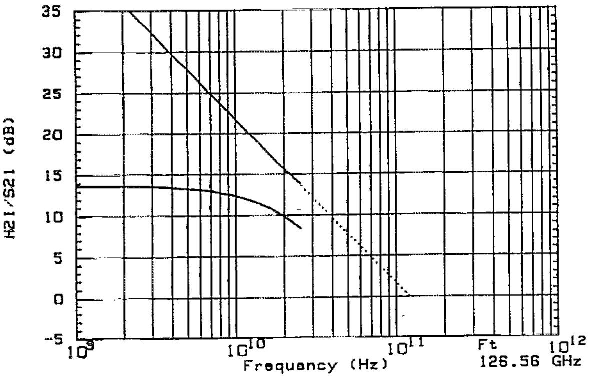

FIG. 2. Current gain $|H_{21}|$ and S_{21} as a function of frequency with $f_t = 126$ GHz for a 0.25×200 μm gate MESFET.

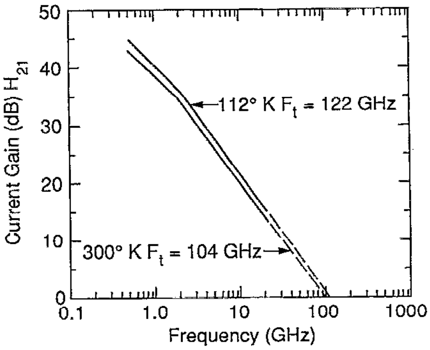

FIG. 4. Current gain $|H_{21}|$ vs frequency with $f_t = 104$ GHz, at 300 K and 122 GHz at 112 K.

slope. The average f_t is 102 GHz and standard deviation is 12 GHz. An f_t of 126 GHz is obtained without pad correction as shown in Fig. 2. By examining one of the incomplete gates of a typical MESFET under a scanning electron microscope (SEM), the gate length is 0.25 μm. Hence, we can correlate the average $f_t = 102$ GHz to the average gate length of 0.25 μm. Therefore, the devices with the $f_t = 126$ GHz are estimated to have a gate length of 0.20 μm. A different device, measured at Cornell University, has an f_t of 118 GHz without pad correction. The f_t is related to the capacitance C_{tot} through the equation $f_t = G_m/(2\pi C_{tot})$. This capacitance includes the parasitic component which is attributed primarily to pad and device geometry. Since C_{tot} values as a function of gate width are colinear, the intercept at zero gate width is equal to the parasitic pad capacitance (0.0169 pF), which is then used to recalculate f_t. The corrected f_t is 150 GHz. This result indicates that millimeter wave performance of our ion implanted InGaAs MESFETs is comparable to the best performance of the InGaAs/GaAs pseudomorphic HEMTs: f_t of 122 GHz for 0.18 μm gate length[5] and f_t of 152 GHz for 0.10–0.15 μm gate length.[6]

The maximum stable gain (GS) and unilateral gain (GU) as a function of frequency for a 0.25×50 micron device are plotted in Fig. 3. The maximum frequency of oscillation, f_{max}, is obtained by extrapolating $|GU|$ to unity gain using a -6 dB/octave slope. An f_{max} of 232 GHz and an f_t of 85 GHz without any pad correction is obtained.

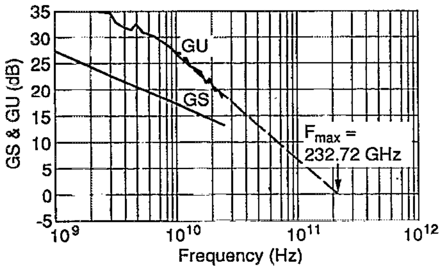

FIG. 3. Maximum stable gain and unilateral gain as a function of frequency with $f_{max} = 232$ GHz for a typical 0.25×50 μm gate, implanted InGaAs MESFET.

The variable temperature Hall effect system from 300 to 4.2 K was used to measure the low-field Hall mobility. The mobility values are 1068 (at 300 K), 1040 (at 110 K), 997 (at 77 K), and 896 $cm^2/V\,s$ (at 4.2 K). The low-temperature mobility results indicate that no two-dimensional electron gases exist in the device.

S parameters from 0.5 to 26 GHz at 300 and at 112 K for a typical 0.25×200 μm gate MESFETs were measured at $V_{gs} = 0$ V and $V_{ds} = 1.6$ V using a custom-built cryogenic high-frequency probe station. The f_t is 105 GHz at 300 K and 122 GHz at 112 K as shown in Fig. 4. The measured f_t at 112 K is 17.3% larger than at 300 K. The parasitic resistances of R_s and R_d are not changing over the temperature in this device since the low-field Hall mobilities and carrier concentrations are nearly the same from Hall measurement at 300 and at 110 K. Therefore, the change in f_t values where $f_t = v_{eff}/(2\pi L_g)$ is attributed mainly from the high-field velocity and not from the low-field mobility.

In conclusion, this work reports an f_t of 126 GHz and an f_{max} of 232 GHz achieved by ion-implanted InGaAs MESFET devices. These results are comparable to the best microwave performance of InGaAs/GaAs pseudomorphic HEMTs. The fact that MESFETs achieved f_t performance similar to HEMTs and the fact that the low-field Hall mobility of MESFETs material is six times lower at 300 K and 30 times lower at 110 K than HEMTs materials lead us to conclude that the average electron velocity under the gate is attributed mainly to high-field electron velocity rather than the low-field electron mobility.[7]

[1] H. D. Shih, B. Kim, K. Bradshaw, and H. Q. Tserng, IEEE Electron Device Lett. **9**, 604 (1988).
[2] M. Feng, G. W. Wang, Y. P. Liaw, R. W. Kaliski, C. Lau, and C. Ito, Appl. Phys. Lett. **55**, 568 (1989).
[3] G. W. Wang, M. Feng, R. W. Kaliski, Y. P. Liaw, C. Lau, and C. Ito IEEE Electron Device Lett. **10**, 449 (1989).
[4] J. C. Huang, M. Zaitlin, W. Hoke, M. Adlerstein, P. Lynman, P. Saledas, G. Jackson, E. Tong, and G. Flynn, IEEE Electron Device Lett. **10**, 511 (1989).
[5] L. D. Nguyen, D. C. Radulescu, P. J. Tasker, W. J. Schaff, and L. F. Eastman, IEEE Electron Device Lett. **9**, 374 (1988).
[6] L. D. Nguyen, P. J. Tasker, D. C. Radulescu, and L. F. Eastman, IEDM Tech. Dig. 176 (1988).
[7] M. Feng, C. L. Lau, V. Eu, and C. Ito, Appl. Phys. Lett. **57**, 1233 (1990).

Published without author corrections