$In_xGa_{1-x}As$ High-Electron Mobility Transistors for Terahertz frequency applications

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***Abstract*—This paper reviews the state-of-the art $In_xGa_{1-x}As$ high electron mobility transistors (HEMTs) for future terahertz frequency operations, aiming to propose roadmap of next-generation $In_xGa_{1-x}As$ HEMT technology. We propose the physics-based compact model for device RF performance such as current gain cut-off frequency (f_T) and maximum osciallation frequency (f_{max}). Also, we quantitantly predict the device performance of sub-30 nm $In_xGa_{1-x}As$ HEMTs with innovatively improving parasitic resistance (R_s) and capacitances components to reach f_T/f_{max} over 1 THz.**

***Keywords*—InGaAs, compound semiconductor, HEMTs, cut-off frequency (f_T), maximum oscillation frequency(f_{max})**

I. Introduction

For several decades, semiconductor-based Terahertz (THz) microelectronics promise to introduce new areas of research and applications in the sub-millimeter-wave region (sub-MMW) and beyond [1-4]. In order to fully benefit the sub-MMW band, it is essential to develop semiconductor transistor technologies with both current gain cut-off frequency (f_T) and maximum oscillation frequency (f_{max}) close to 1 THz. To improve high-frequency characteristics of semiconductor transistor, historically, a path to improve f_T/f_{max} in InGaAs high-electron-mobility transistors (HEMTs) was to reduce the physical gate length (L_g) down to sub-30 nm, while minimizing all of the parasitic components such as series resistance and gate-fringing capacitance. The other is to introduce high carrier mobility channel material. In this regard, indium-rich $In_xGa_{1-x}As$ HEMTs have offered the best balance of f_T and f_{max} to date [5-6].

II. Developments and Analysis in InGaAs HEMTs

A. State-of-the art InGaAs HEMTs

Figure 1 shows the cross sectional schematic view of a conventional $In_xGa_{1-x}As$ HEMT. Semi-insulating (S.I) InP wafer of 3-inch size is commonly used in the fabrication of $In_xGa_{1-x}As$ HEMTs. It is imperative to develop InGaAs HEMTs of gate length less than 30 nm for terahertz wave applications. $In_xGa_{1-x}As$ HEMT technology could already achieve a f_T of 738 GHz [5] and f_{max} over 1 THz [3] which raises the hope for its use in future terahertz wave applications. **Figure 2** plots $|h_{21}|^2$ and U_g for state-of-the art HEMT technology with various QW channel structure and gate length scaling from 300 to 20 nm [5]. As expected, both f_T and f_{max} improved with reduction of L_g. The composite-$In_{0.8}Ga_{0.2}As$ HEMT demonstrated the values of f_T = 738 GHz and f_{max} = 492 GHz. **Figure 3** shows the dependence of f_T and f_{max} for all the devices upon L_g.

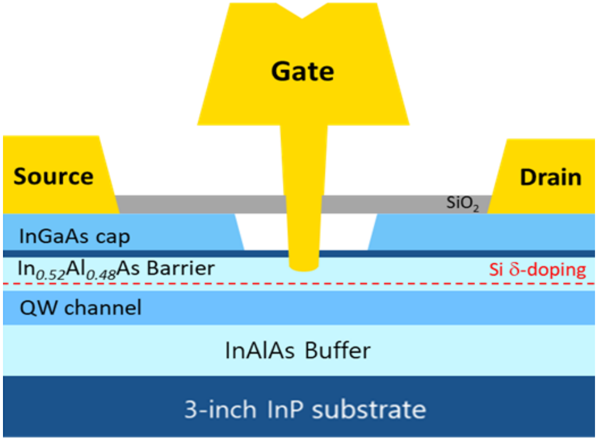

Figure 1. Schematic of conventional $In_xGa_{1-x}As$ HEMT.

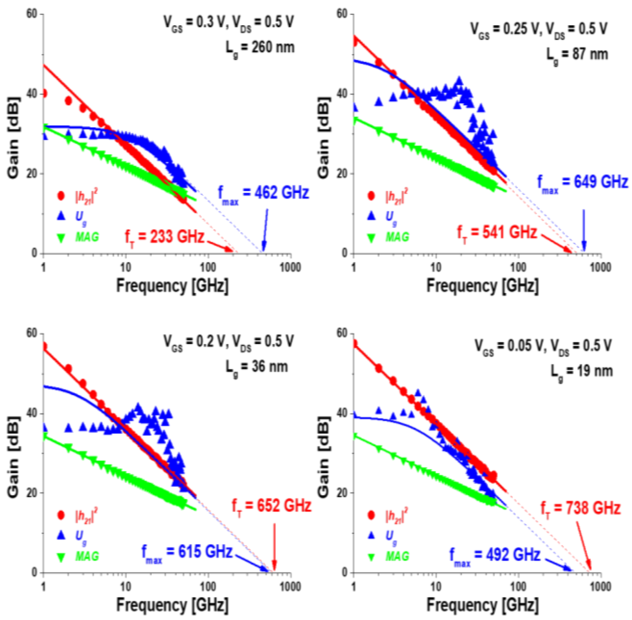

Figure 2. Measured RF gains ($|h_{21}|^2$, U_g and MAG) versus frequency near the g_m peak gate voltage and at V_{DS} = 0.5 V.

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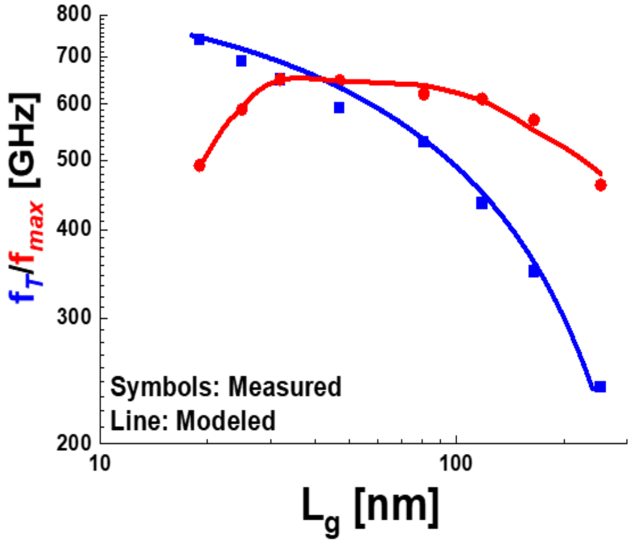

Figure 3. Measured (symbols) and modeled (lines) f_T /f_{max} against L_g.

B. f_T/f_{max} phyiscal model

In an effort to understand the scaling behavior of f_T and f_{max}, the compact f_T/f_{max} physical model using physical/geometrical parameters. The first-order expressions for f_T and f_{max} are given as follows [7-8]:

$$f_T = \frac{1}{2\pi}\frac{g_{mi}}{C_{gs}+C_{gd}+g_{mi}(R_S+R_D)\left\{C_{gs}+\left(C_{gs}+C_{gd}\right)\frac{g_{oi}}{g_{mi}}\right\}} \quad (1)$$

$$f_{max} = \frac{f_T}{2\sqrt{(R_i+R_S+R_g)\cdot g_{oi}+(2\pi f_T)\cdot R_g\cdot C_{gd}}} \quad (2)$$

The values of g_{mi}, R_S, and R_D were extracted as in R_S analysis [9] and g_m physical modeling [10], and g_{oi} was given by the product of g_{mi} and *DIBL* was used. As in [5], C_{gs} consisted of $C_{gs\_areal}\times L_g$ (intrinsic) and C_{gs_ext} (extrinsic) components, where C_{gs_ext} was extracted separately at a pinch-off bias condition since C_{gs} was dominated by extrinsic components. The same analysis was performed for C_{gd}.

Modeled f_T and f_{max} are included as lines in **Figure 3**, where the approach in this work explains the dependence of f_T and f_{max} of all the devices upon L_g from 300 to 20 nm. The proposed f_T/f_{max} model is capable of explaining the measured f_T and f_{max} for all the devices universally.

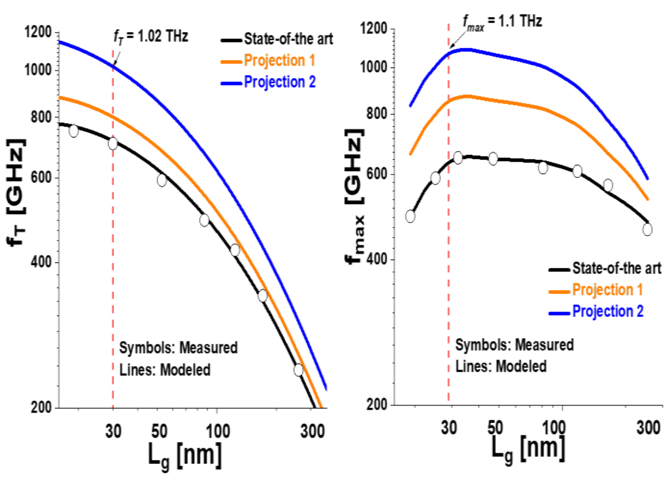

Figure 4. f_T/f_{max} modeling result of device technology improvement (model projection).

III. $In_xGa_{1-x}As$ HEMTs for terahertz f_T/f_{max} performacne

The proposed physical f_T/f_{max} model accurately explain the measured f_T/f_{max} for all of L_g. So, by using physical f_T/f_{max} model, projection of the f_T/f_{max} characteristics of a device with improvement such as carrier transport property, reduction of R_S, and g_{oi} improvement, could be compared to current state-of-the art $In_xGa_{1-x}As$ HEMTs devices. In projection 1, when R_S was reduced by 30%, it can be projected to improvement of about 15 % compared to conventional state-of-the art devices with f_T/f_{max} = 800/870 GHz at L_g = 30 nm. In projection 2, when R_S and extrinsic gate capacitance (C_{g_ext}) were reduced to less than half, projected a value of f_T/f_{max} is 1.02/1.09 THz with improvement of about 40 % compared to state-of-the art $In_xGa_{1-x}As$ HEMT device. **Figure 4** exhibit projection results of f_T/f_{max} as a function of L_g with current state-of-the art HEMTs (black), R_s reduction (projection 1, orange), R_s and C_{g_ext} reduction (projection 2, blue). For future THz operation device technology, it is important to demonstrate sub-30 nm $In_xGa_{1-x}As$ HEMTs with innovatively improving parasitic resistance components (R_s) and, also, reduction of parasitic gate capacitance to reach f_T/f_{max} over 1 THz, as predicted f_T/f_{max} performance through physical modeling.

IV. Conclusion

In this paper, we reviewed the state-of-the art $In_xGa_{1-x}As$ high electron mobility transistors (HEMTs) for future terahertz frequency operations. Also, we modeled physically experimental RF FOMs (Figure of Merits) with state-of-the art $In_xGa_{1-x}As$ HEMT technology. Also, we quantitantly predict the device performance of sub-30 nm $In_xGa_{1-x}As$ HEMTs with innovatively improving parasitic resistance components (R_s) to reach f_T/f_{max} over 1 THz.

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