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## **DC and Microwave Characteristics of Sub-micron AlGaIn/GaN High-Electron-Mobility Transistors on 8-inch Si (111) Substrate**

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We report for the first time the DC and microwave characteristics of sub-micron gate (~0.3  $\mu\text{m}$ ) AlGaIn/GaN high-electron-mobility transistors (HEMTs) on 8-inch diameter Si (111) substrate. The fabricated sub-micron gate devices on crack-free AlGaIn/GaN HEMT structures exhibited good pinch-off characteristics with a maximum drain current density of 853 mA/mm and a maximum extrinsic transconductance of 180 mS/mm. The device exhibited unit gain cut-off frequency of 28 GHz, maximum oscillation frequency of 64 GHz and OFF-state breakdown voltage of 60 V. This work demonstrates the feasibility of achieving good performance AlGaIn/GaN HEMTs on 8-inch diameter Si (111) for low-cost high-frequency and high-power switching applications.

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## 1. Introduction

GaN is a promising wide-band-gap semiconductor for next-generation high-frequency and high-power switching devices, because of its high saturation velocity at high electric field, high breakdown electric field, and high electron mobility. So far, different groups have demonstrated excellent high-frequency, high microwave power and power switching devices using GaN high-electron-mobility transistors (HEMTs) that break the Si limit.<sup>1-7)</sup> Major industry players are now developing the AlGaIn/GaN HEMT technology on 4- to 6-inch diameter Si(111)-substrates for high-power switching applications. Growing GaN on silicon offers the advantages of low-cost and large diameter wafers which make manufacturing costs of GaN-on-Si potentially competitive with existing Si and SiC technologies. Using larger 8-inch silicon wafers for GaN growth also offers the opportunity to exploit existing 8-inch foundries that are fully depreciated and underutilized. However GaN growth on 8-inch silicon is quite challenging because the larger wafer diameter leads to problems such as high wafer bow which can lead to non-uniform material properties and make further device processing difficult. Recently, growth of GaN layers on 6- and 8-inch diameter Si (111) substrates has been realized.<sup>8-12)</sup> More recently, Chen et al.<sup>13)</sup> demonstrated AlGaIn/GaN/AlGaIn double-heterostructures on a 8-inch diameter Si (111) substrate with the electron mobility of 1766 cm<sup>2</sup>/V.s. However, to the best of our knowledge, the electrical performances of transistors using GaN-based HEMT structures grown on a 8-inch diameter Si (111) substrate have not been so far reported. In this paper, for the first time, we report both DC and RF performance of sub-micron gate HEMTs, where the AlGaIn/GaN heterostructures are grown on a 8-inch diameter Si (111) substrate by a metalorganic chemical vapor deposition (MOCVD) technique.

## 2. Experimental

Figure 1 (a) shows the photograph of crack-free AlGaIn/GaN HEMT structures grown on a full 8-inch diameter Si (111) with a starting substrate resistivity of  $\sim 40 \text{ } \Omega\text{-cm}$  using the MOCVD system (Veeco™ TurboDisk k465i). The device structure: *i*-GaIn (2nm)/*i*-Al<sub>0.17</sub>Ga<sub>0.83</sub>In(18nm)/GaN(1050nm)/AlIn(10nm)/GaN(870nm)/AlIn (10nm)/Al<sub>1-x</sub>Ga<sub>x</sub>In (1000 nm) multiple layers/AlIn(100 nm)/8-inch Si (111). All the epi-layer thicknesses were confirmed by cross-sectional high-angle annular dark-field scanning transmission electron microscopy (HAADF-STEM). Figure 2 shows the cross-sectional HAADF-STEM image of the (a) full HEMT structure (b) GaIn cap + AlGaIn barrier layer (c) stress mitigation layers grown on 8-inch diameter Si (111). Total buffer thickness is  $\sim 2.9 \text{ } \mu\text{m}$ . The average edge- and screw-dislocation densities measured on the samples were in the order of  $1.5 \times 10^9 \text{ cm}^{-2}$  and  $5.3 \times 10^8 \text{ cm}^{-2}$ , respectively. The details of the epitaxial growth and characterization of such AlGaIn/GaN heterostructures will be discussed elsewhere. Figure 1(b) shows room temperature two-dimensional-electron-gas (2DEG) mobility ( $\mu_{\text{H}}$ ) and sheet resistance ( $R_{\text{sh}}$ ) of AlGaIn/GaN HEMT for five samples taken from the different location of 8-inch wafer (see Figure 1(a)). The HEMT structure exhibited the average  $\mu_{\text{H}}$  of  $1550 \text{ cm}^2\text{V}^{-1}\text{s}^{-1}$ , sheet carrier concentration ( $n_{\text{s}}$ ) of  $0.84 \times 10^{13} \text{ cm}^{-2}$ , and an average  $R_{\text{sh}}$  of  $<400 \text{ ohm/sq}$ . The product  $n_{\text{s}} \times \mu_{\text{H}}$  is  $1.26 \times 10^{16} \text{ V}^{-1}\text{s}^{-1}$  and the surface RMS roughness of AlGaIn/GaN HEMT structure is 0.25 nm which are equivalent to the previously reported data in the literature in the cases of AlGaIn/GaN heterostructures grown on 4- to 6-inch Si substrates.<sup>10,14,15</sup> To fabricate the sub-micron gate HEMTs, the 8-inch AlGaIn/GaN epiwafers was diced into small sizes for electron-beam lithography and subsequent device processing steps.

The mesa isolation for HEMT device fabrication was accomplished by dry etching down to GaIn buffer layer using Cl<sub>2</sub>/BCl<sub>3</sub> plasma-based inductive coupled plasma (ICP) system.

The Ohmic contacts were realized using a 4-layer metallization scheme (Ti/Al/Ni/Au) followed by rapid thermal annealing at 825 °C for 30s. The measured contact resistance was about 1.8  $\Omega$ -mm. Following the Ohmic patterns, the mushroom gate was defined by electron beam lithography. Evaporation and lift-off of Ni/Au was used to form the Schottky-gates. The device processing details can be found elsewhere.<sup>15)</sup> The dimensions of the devices used in this study are as follows: source-gate distance,  $L_{sg} = 0.8 \mu\text{m}$ ; gate width,  $W_g = (2 \times 25) \mu\text{m}$ ; gate length,  $L_g = 0.3 \mu\text{m}$ ; gate-drain distance,  $L_{gd} = 1.25 \mu\text{m}$  and gate-gate distance,  $L_{gg} = 12 \mu\text{m}$ . On-wafer DC and small-signal microwave characteristics were performed to characterize the fabricated devices on un-thinned Si substrate using B1500 semiconductor parameter analyzer and 8510c Vector Network Analyzer, respectively. To measure the 2DEG density as a function of channel depth, capacitance-voltage (C-V) measurements were carried out at 1 MHz on the Schottky diodes fabricated on the same sample.<sup>16)</sup> Both lateral buffer breakdown voltage ( $BV_{\text{Buff}}$ ) and three terminal breakdown voltage ( $BV_{\text{gd}}$ ) was obtained by a fixed current compliance of 0.5 mA/mm.

### 3. Results and Discussions

Figure 3 (a) shows the channel-current and buffer-leakage-current of AlGaN/GaN HEMTs. The measured  $I_{\text{ON}}/I_{\text{OFF}}$  ratio is  $1.36 \times 10^5$  at a bias voltage of 100 V. The 2DEG density of around  $1.8 \times 10^{20} \text{ cm}^{-3}$  peaks at a depth of 20.2 nm from the surface of AlGaN/GaN HEMT structure (See inset of Fig 3(a)). The 2DEG profile depth matches well with the barrier layer thickness as seen from our STEM imaging (see Figure 2). From this it is confirmed that the existence of 2DEG between the AlGaN barrier and GaN buffer layer. The background carrier density in the buffer GaN is about  $4.98 \times 10^{14} \text{ cm}^{-3}$ , and this value is comparable to the HEMT structures previously reported on 4-inch Si substrate.<sup>14,15)</sup> The  $(N_{\text{D2DEG}})_{\text{peak}}/(N_{\text{D2DEG}})_{\text{min}}$  ratio is  $3.6 \times 10^5$  which correlates well with the channel  $I_{\text{ON}}/I_{\text{OFF}}$  ratio in such devices. Figure 3 (b) shows the  $BV_{\text{gd}}$  and the  $BV_{\text{Buff}}$  characteristics of

AlGaIn/GaN HEMTs. The 0.3- $\mu\text{m}$ -gate HEMTs with  $W_g/L_{sg}/L_{gd}/L_{gg} = (2 \times 25)/0.8/2/12 \mu\text{m}$  exhibited the  $BV_{gd}$  of 60 V. However, the 2.0- $\mu\text{m}$ -gate HEMTs with  $W_g/L_g/L_{sg}/L_{gd} = (1 \times 80)/2/2/6 \mu\text{m}$  exhibited the  $BV_{gd}$  of 188 V which is close to the  $BV_{\text{Buff}}$  value. Equal breakdown strength ( $BV_{gd}/L_{gd}$ ) of  $\sim 0.3$  MV/cm has been occurred for both 0.3- $\mu\text{m}$ -gate and 2.0- $\mu\text{m}$ -gate AlGaIn/GaN HEMTs. The Schottky-gate of the device exhibited the reverse gate-leakage current of  $4.85 \times 10^{-6}$  mA/mm at -20V (see inset of Fig 3(b)). From this it is clear that the device breakdown was not suffered by the gate-leakage current. Hence, the device  $BV_{gd}$  is limited by the GaN buffer thickness and its crystalline quality.<sup>1)</sup> This has been further confirmed by measuring the  $BV_{\text{Buff}}$  between the two adjacent ohmic pads ( $50 \mu\text{m} \times 50 \mu\text{m}$ ) with 10  $\mu\text{m}$  gap which can withstand up to 192 V. Thick high crystalline quality GaN buffer layers are often desired to increase the  $BV_{gd}$  of the devices.<sup>1)</sup> However, in such a 8-inch GaN-on-Si platform, to increase the breakdown voltage, it is also necessary to improve the crystalline quality of the full nitride stack on Si substrate. The presence of a higher screw- and edge- dislocation density at the hetero-interfaces usually leads to a lower  $BV_{\text{Buff}}$ .

Figure 4 shows  $I_{DS}-V_{DS}$  (a) and transfer characteristics (b) of AlGaIn/GaN HEMTs on 8-inch diameter Si (111). The device exhibited good pinch-off characteristics with the maximum drain current ( $I_{D\text{max}}$ ) of 853 mA/mm and maximum extrinsic transconductance ( $g_{m\text{max}}$ ) of 180 mS/mm at  $V_g = -2.3$  V and  $V_D = 10$  V. The device threshold voltage is -3.8 V. Figure 5 (a) shows the small-signal microwave performance of  $(2 \times 75) \mu\text{m}$  wide-gate AlGaIn/GaN HEMTs on 8-inch Si (111) with  $L_{gd}$  of  $2 \mu\text{m}$ . A unit current gain cut-off frequency ( $f_T$ ) of 28 GHz and a maximum oscillation frequency ( $f_{\text{max}}$ ) of 64 GHz was achieved for these devices at  $V_D = 10$  V and  $V_g = -2.4$  V. The  $f_T \times L_g$  is 8.4 GHz. $\mu\text{m}$  which is comparable to the AlGaIn/GaN HEMTs fabricated on smaller diameter Si substrate.<sup>15)</sup> The trend of  $f_T$  and  $f_{\text{max}}$  for different bias conditions are also shown in figure 5 (b) which is

consistent with the device transfer characteristics (See Figure 4 (b)). A conductive buffer layer can introduce parasitic capacitances (extrinsic capacitances), which lower the available power gains of the HEMT at high frequencies. The ratio of  $f_{\max}/f_T = 2$  to 2.66 which supports the fact that the grown buffer GaN does not have an additional charge coupling effects.<sup>17)</sup>

#### 4. Conclusions

The 0.3- $\mu\text{m}$ -gate HEMTs with maximum drain current of 853 mA/mm and extrinsic transconductance of 180 mS/mm were demonstrated for the first time on undoped AlGaIn/GaN heterostructure on a 8-inch Si(111) substrate. The 2- $\mu\text{m}$ -gate HEMT in the same device structure exhibited the  $BV_{\text{gd}}$  of 188 V which is almost equivalent to the lateral  $BV_{\text{Buff}}$  of 192 V. The 0.3  $\mu\text{m}$ -gate HEMT exhibited  $f_T$  of 28 GHz,  $f_{\max}$  of 64 GHz and  $BV_{\text{gd}}$  of 60 V. The observed  $f_{\max}/f_T > 2$  to 2.66 is due to the occurrence of good quality buffer GaN with low buffer leakage current ( $4.8 \times 10^{-3}$  mA/mm @100 V). Our results show the feasibility of growing device quality AlGaIn/GaN HEMT structure on 8-inch diameter Si(111) for low-cost high-frequency and high-power switching applications.

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### Figure Captions

Figure 1. (a) Picture of as grown GaN HEMT structure on 8-inch Si (111), (b) Room temperature 2DEG Hall mobility and sheet resistance from the centre to edge (samples 1 to 5) of GaN HEMT structure on 8-inch Si(111) wafer, (c) AFM micrograph with  $5\ \mu\text{m} \times 5\ \mu\text{m}$  scan area (RMS roughness=0.25 nm)

Figure 2. (a) Typical cross-sectional high-angle annular dark-field scanning transmission electron microscopy (HAADF-STEM) image of the full HEMT structure on 8-inch diameter Si(111) substrate. (b) HAADF-STEM z-contrast image of the same sample showing GaN cap layer and AlGaN barrier layer (c) HAADF-STEM z-contrast image of the same sample showing stress mitigation layers (AlGaN multi layers (MLs) on a 110 nm-thick AlN nucleation layer) on 8-inch Si (111).

Figure 3. (a) 2DEG carrier profiling for AlGaN/GaN HEMTs measured on Schottky diodes by C-V measurements Channel and buffer leakage current characteristics of AlGaN/GaN HEMTs. (b)  $BV_{gd}$  and lateral  $BV_{\text{Buff}}$  (gap=10  $\mu\text{m}$ ) characteristics of GaN HEMTs. Inset: Two terminal reverse and forward gate-drain characteristics of GaN HEMTs with the device dimensions of  $W_g/L_g/L_{sg}/L_{gd}= 80/2/2/6\ \mu\text{m}$ .

Figure 4. (a)  $I_{DS}-V_{DS}$  and (b) transfer characteristics of AlGaN/GaN HEMTs on 8-inch diameter Si (111) substrate.

Figure 5. (a) Small-signal microwave characteristics of AlGaN/GaN HEMTs with the device dimensions of  $W_g/L_g/L_{sg}/L_{gd}= (2 \times 75)/0.3/0.8/2\ \mu\text{m}$ . (b)  $f_T$  and  $f_{\text{max}}$  for different gate and drain biases ( $V_D=4$  to 10 V).

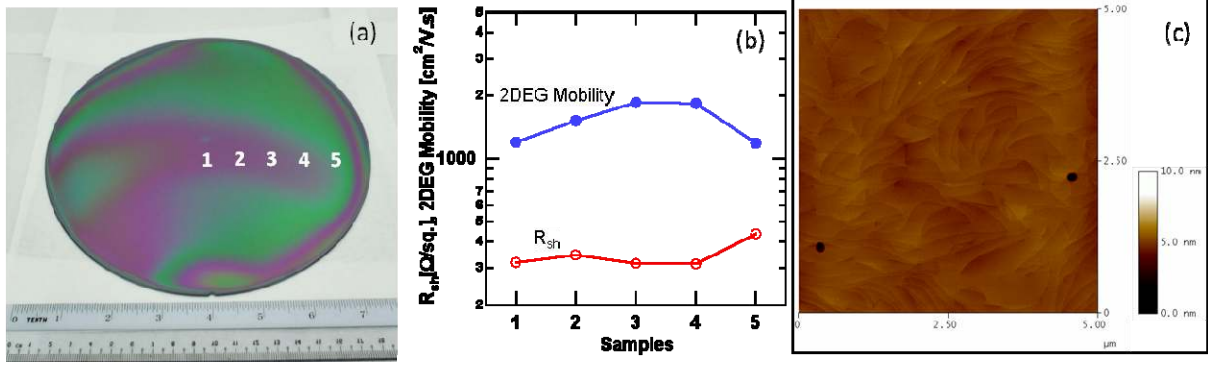


Figure 1. Arulkumaran et al.

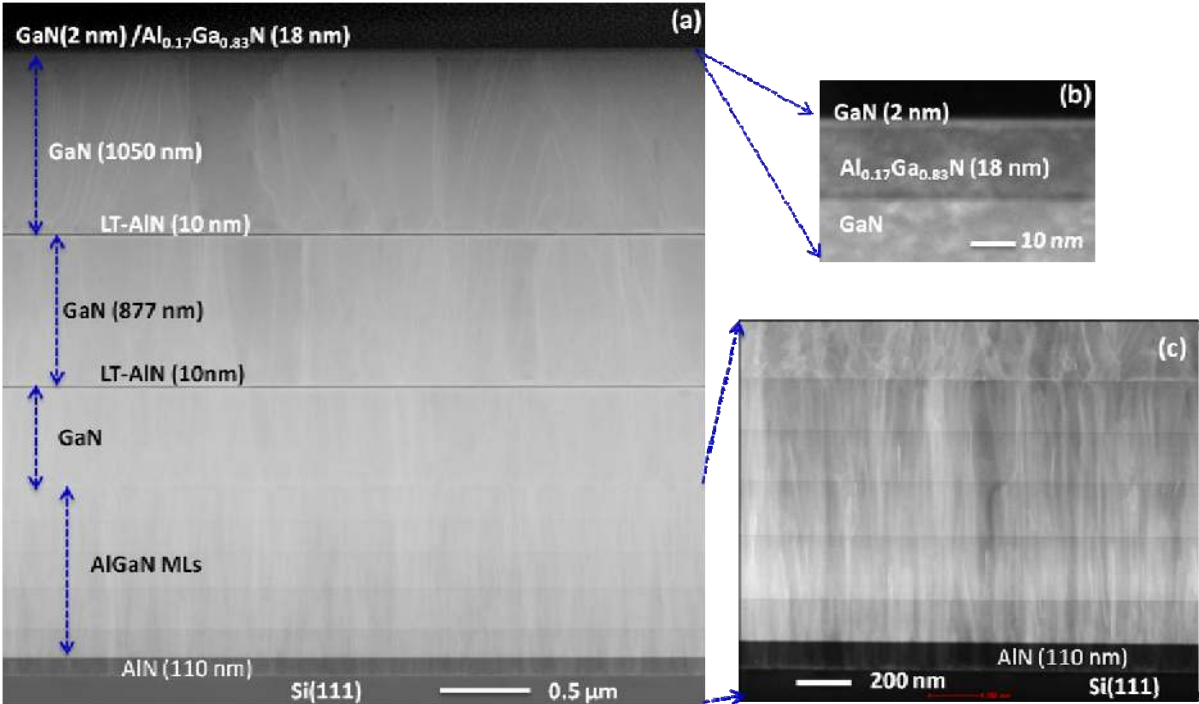


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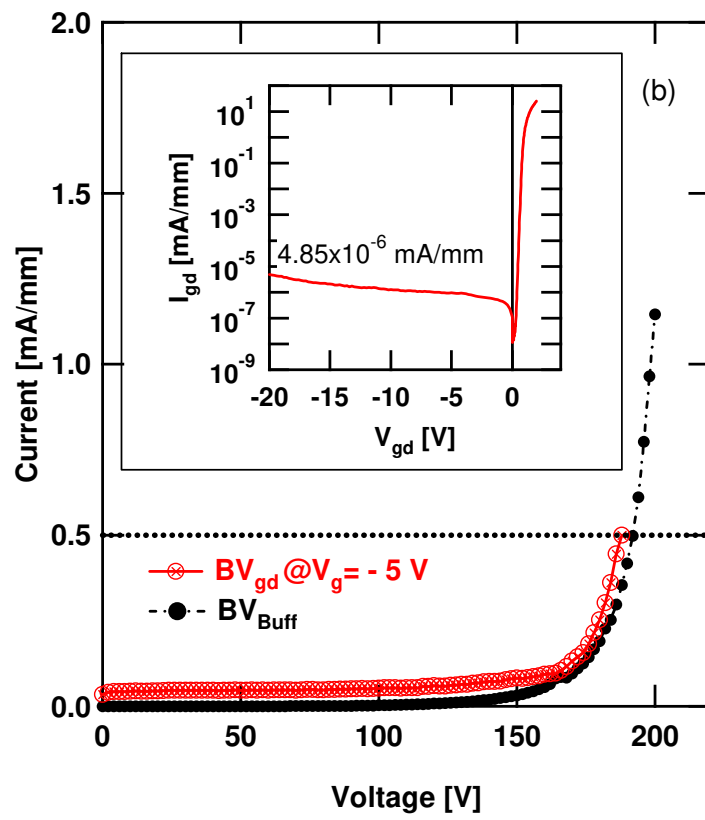
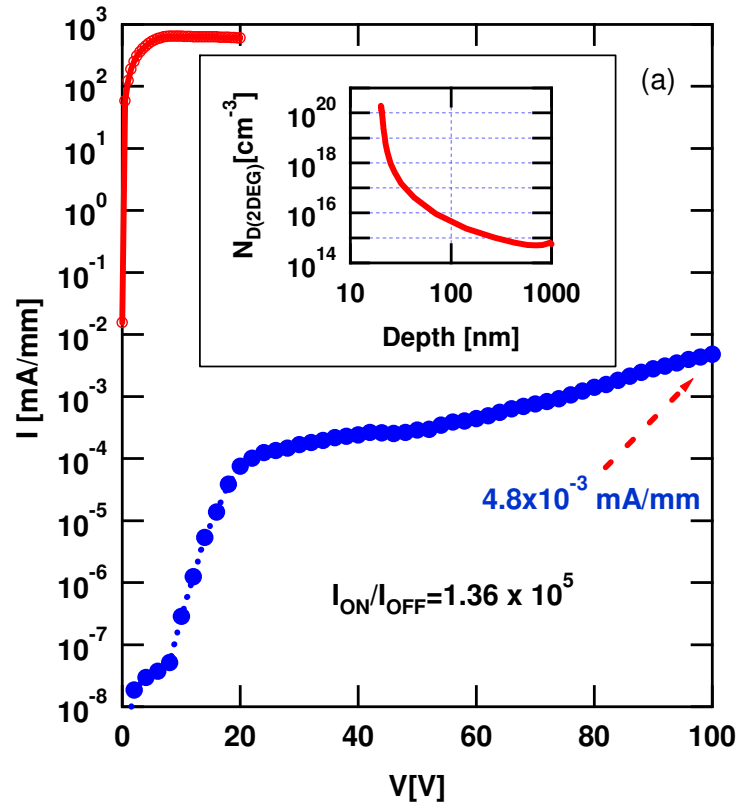


Figure 3. S. Arulkumaran et al.

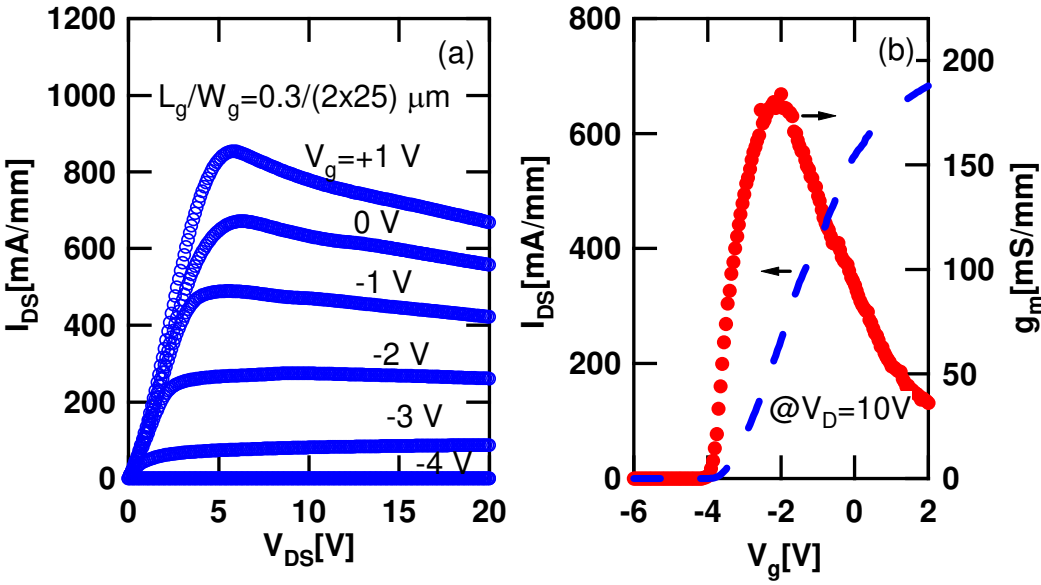


Figure 4. S. Arulkumaran et al.

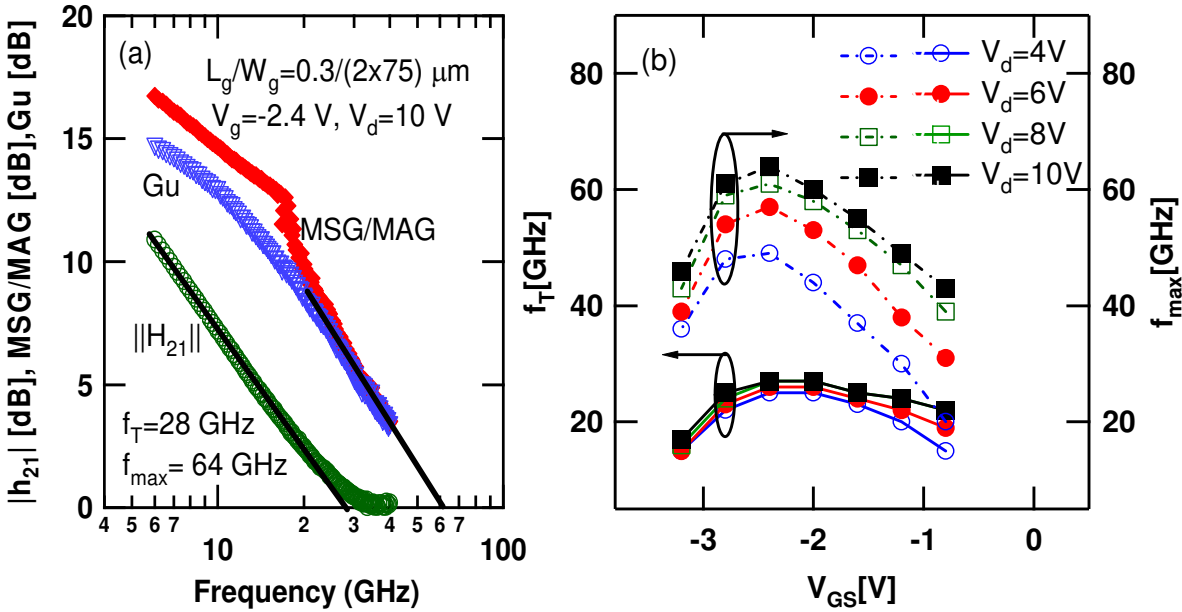


Figure 5. S. Arulkumaran et al.