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Cryogenic InGaAs HEMTs for LNA and routing circuits in Quantum Computing

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Abstract

Cryogenic RF transistors and routing circuits operating with extremely low power are essential as control/readout electronics for future large-scale quantum computing systems. In this work, we demonstrate 3D stackable InGaAs HEMT-based cryogenic RF transistors and routing circuits integrated with Nb superconductors for ultra-low power operation.

1. Introduction

To realize large-scale quantum computers with thousands or millions of qubits, “cold” electronics operating at low-power and cryogenic temperatures will be required. This will maintain the fidelity of the qubits and allow put this system under state-of-the-art cooling capabilities. Furthermore, to provide the ultimate accessibility of the electronics to qubits, 3D integration potential should be considered for hardware development. Therefore, we have recently developed 3D stackable InGaAs HEMT-based cryogenic transistors for low-noise amplifiers and routing circuits at cryogenic temperatures as shown in Fig. 1 [1-3]. First, the epitaxial layer of the HEMT has been optimized for the cryogenic operation to minimize parasitic resistance [1]. Second, we proposed to use the 2DEG channel of the InGaAs HEMT for routing circuits especially at local interconnect with the control gate because carrier mobility is increased at cryogenic temperature due to the reduced phonon scattering, resulting in the reduced resistance comparable to the metallic interconnect by eliminating considerable contact resistance between InGaAs contact layer and metal [2]. Finally, we have extended our routing approaches using the superconductor for global interconnect [3].

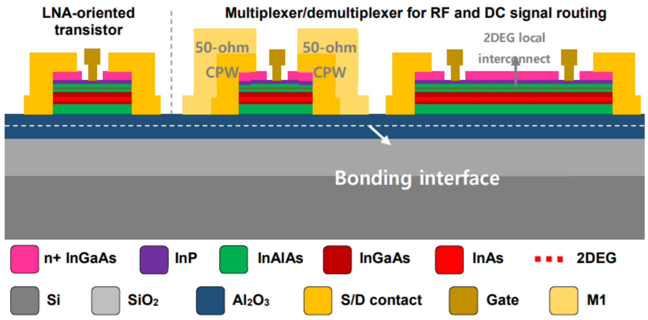

Fig. 1 . Schematic cross-section of the cryogenic electronics for biasing, control, and readout. LNA transistors, RF switch matrix, and demultiplexer are monolithically fabricated on the same substrate.

2. Experiments and discussions

A. RF performance of InGaAs HEMT for LNA

Fig. 2 shows a schematic cross-section of the InGaAs HEMTs and carrier transports at cryogenic temperature will be bottlenecked by barrier resistance ($R_{barrier}$) from the layer structure and its band diagram because thermionic transport will be significantly suppressed. To minimize the $R_{barrier}$, we explored barrier thickness scaling down to 6 nm with an additional spacer 3 nm. From this engineering, we realized high on-current and transconductance without noticeable penalty in the gate leakage as shown in Fig. 3. This allows record-high RF performance represented by cutoff frequency in Fig. 4. It should be noted that ultra-low power operation is feasible at the given operating frequency of around 10 GHz in quantum computing.

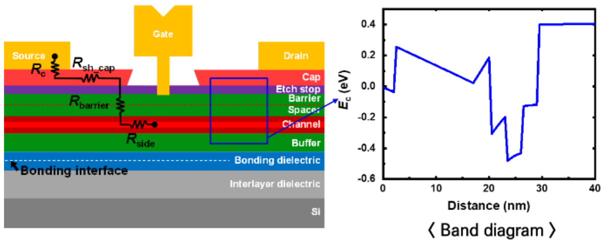

Fig. 2 Simplified illustration of the InGaAs HEMTs and parasitic resistance components with band diagram.

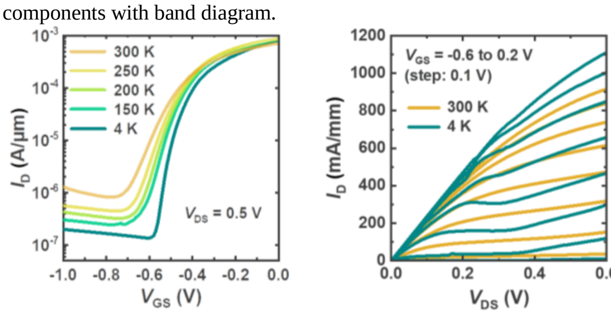

Fig. 3 Transfer and output characteristics of InGaAs HEMT-based RF transistor with L_G =70 nm and W_G = 2×20 μm at different temperatures.

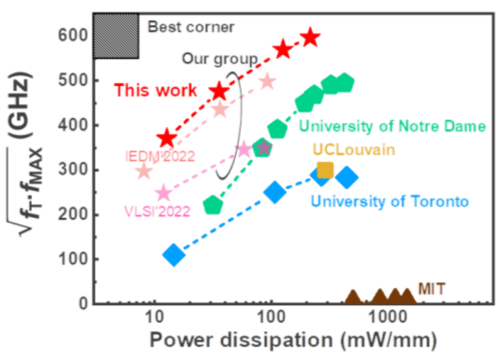

Fig. 4 The RF performance (average cutoff frequency) benchmarking of state-of-the-art cryogenic RF transistors versus power consumption.

B. Routing capability of InGaAs HEMT for DC signal

Fig. 2(a) and (b) show SEM images of 3D stackable InGaAs HEMT-based cryogenic RF transistor and routing circuit with Nb superconductor fabricated on the same substrate. To examine the DC routing capability, we evaluated the 1-to-4 routing circuit consisting of one input and 4 output paths with 4 control gates. Fig. 6 shows the time domain input and output results when different routing paths are set. To route the input signal to the Y_{11} output, we set SA_1 to on-state and SA_2 to off-state. Subsequently, on-state pulse bias is applied to SB_1 and off-state bias is applied to SB_2. Then, we can observe the out signal at Y_{11}. And there is no signal at other outputs. Fig. 6 shows the measured output current of each output for variation of input signals to control gates, showing excellent selectivity in each configuration and low variance among the outputs.

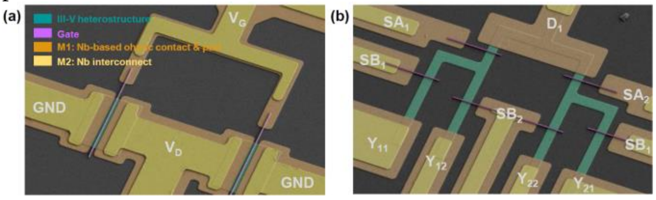

Fig. 5 False colored SEM image of 3D stacked InGaAs HEMT-based (a) two-finger cryogenic RF transistor and (b) cryogenic 1-to-4 routing circuits with III-V heterostructure local interconnect and Nb superconductor global interconnect.

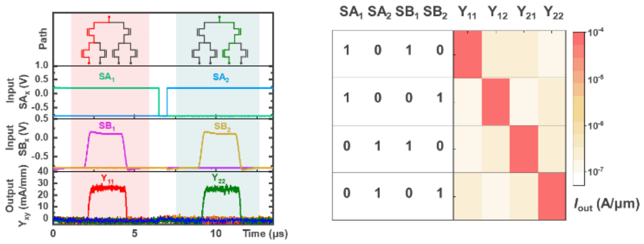

Fig. 6 Time domain input and output results when different input signals are set and the output current of each output for variation of input signals.

B. Routing capability of InGaAs HEMT for RF signal

RF signal is used to read out and control the qubits in quantum computing. Therefore, RF signal routing is also very important. We also evaluated this capability of InGaAs HEMT-based routing circuits according to the simplified circuit schematic in Fig. 7. Two InGaAs quantum well HEMTs with 2DEG were used to selectively connect or isolate each of the two-port from the common port. In the on-state, the RF signal can be transmitted through the input CPW line, 2DEG, and output CPW line. However, in the off-state

, the negative voltage of the control gate depletes the 2DEG at the interface, the removing RF signal path and turning off the switch. The S-parameter was measured up to 10 GHz which is a commonly used band in quantum computing systems. The insertion loss was between 3.6 and 5.3 dB over the 4–8 GHz and isolation in the off-state was more than 40 dB over the 4–8 GHz. A significant difference between insertion loss and isolation above 45 dB was obtained in the corresponding frequency, appropriate to RF signal routing for the future large-signal quantum computing system.

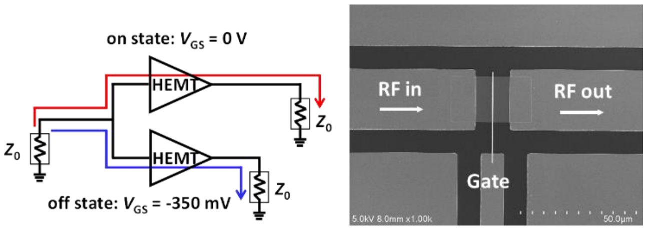

Fig. 7 Simplified schematic and SEM image of the fabricated device of 1-to-2 switch matrix based on InGaAs HEMT for RF signal routing.

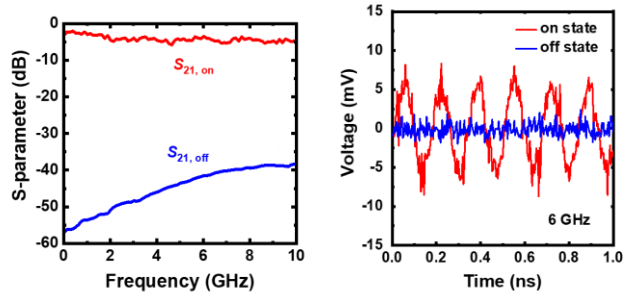

Fig. 8 S-parameters of cryogenic RF switch matrix with the different state and output waveform of cryogenic RF switch matrix at 5 K with a 6-GHz input signal where one path is in the on state and the other path is (a) off

3. Conclusions

As an important building block for future large-scale quantum computing, we have developed and demonstrated the 3D stacked InGaAs-based cryogenic RF transistors and routing circuits. From the layer design/engineering for cryogenic operation, we achieved RF transistors holding record-high RF performances. Furthermore, we experimentally demonstrated the low resistive InGaAs 2DEG and Nb superconductor integrated routing circuits both for DC and RF signal routing. These results provide a path to ultra-low-power control/readout electronics for large-signal quantum signal processing.

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References

[1] J. Jeong *et al.*, *Symposium on VLSI Technology and Circuits*, p. 328 (2022).

[2] J. Jeong *et al.*, *International electron device meetings (IEDM)*, p. 87 (2022).

[3] J. Jeong *et al.*, *Symposium on VLSI Technology and Circuits*, T7-5 (2023).