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Device Scaling and Prospect of GaN FET

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1. Introduction

For these 30 years, not only silicon VLSI devices, but also almost every electron device pursued to miniaturize their sizes for higher speed operations. According to the scaling rule [1], the supply voltages should also be reduced to keep the field strength constant. Since supply voltage reduction has been also required for low power operation of VLSI chips, low voltage operation has been one of the most important issues for electron devices.

However, it has been forecasted that there is a lower limit of supply voltage due to the statistical nature of carriers in semiconductors. Since the applicable voltage is proportional to breakdown field strength of the material, wide band gap semiconductors become attractive to break the limit.

In this paper, the voltage limit in device scaling and the device speed at the voltage limit will be explained Then, the prospects of GaN based MMIC will be presented.

2. Miniaturization Limits for VLSI

It has been said that there will be three fundamental limits of component miniaturizations in computing systems, thermal limit, quantum limit and voltage limit [2].

Thermal limit is the minimum energy required for logic circuit switching, which is expressed as,

$$E_{SW} > kT\log(MTBF/\tau_{SW}). \qquad (1)$$

Here, *MTBF* is the mean time between failure, τ_{SW} is the switching time. This limit is imposed only on gates where data is stored in capacitors without regenerating DC power, like CMOS VLSI circuit.

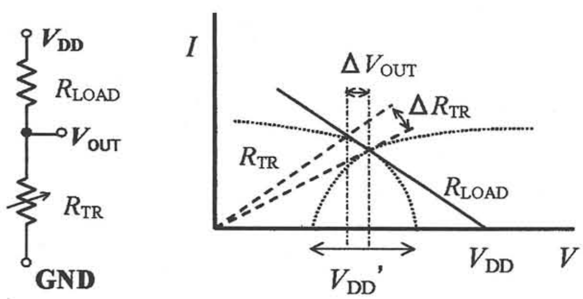

Fig.1 Model for Resistor Load Amplifier
When non-linear resistors are used, the supply voltage can be reduced from V_{DD} to V_{DD}'.

Quantum limit comes from wave nature of electrons. To prevent the tunneling through barriers such as the depletion region around the drain, the barrier width must be much larger than the critical thickness given by,

$$W_B = \frac{1}{2}\sqrt{\hbar^2/2mE_B}. \qquad (2)$$

Here, m is the electron effective mass and E_B is the barrier height, which is the band gap in depletion region. Due to the wide band gap energy, that on GaN will be the smallest among practical semiconductors. However, the values are still far compared with other limitations.

3. Voltage Limit

Transistor current is controlled by potential variation at the channel through input terminal voltage. The carrier distribution in semiconductors is governed by Maxwell-Boltzmann distribution. So, the transistor resistance R_{TR} is exponentially dependent on input voltage V_{IN} as,

$$R_{TR} = R_O \exp\left(-\frac{qV_{IN}}{\alpha kT}\right), \qquad (3)$$

where q is electron charge, k is Boltzmann constant and T is the temperature. The factor α is due to indirect control of channel fermi level by the input signal and is always more than 1.

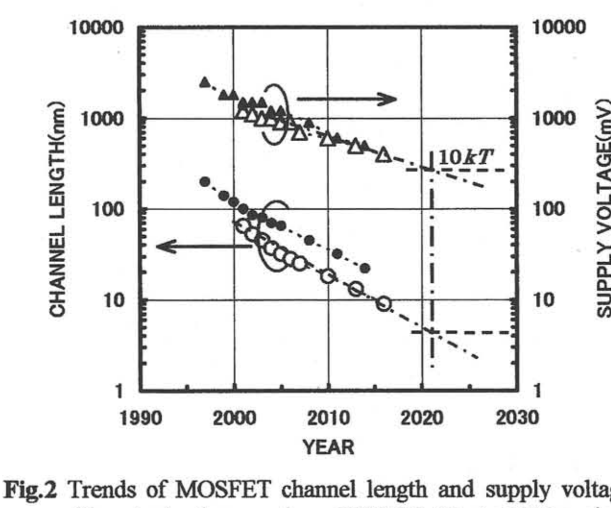

Fig.2 Trends of MOSFET channel length and supply voltage on silicon technology roadmap ITRS [4]. (●,▲; 1999 projection, and ○,△; 2001 projection)

Fig.1 show the model of resistor load amplifier. Applying Eq.(3), the minimum supply voltage is $4G\alpha kT$ for analog amplifier with gain of G, and $4n\alpha kT$ for NAND or NOR logic gates with n-inputs [3].

When current saturation-type resistors like FETs are used, the supply voltages can be further reduced, but the saturation characteristics is again governed by Maxwell-Boltzmann distribution. Considering these, $10kT$ or 250mV will be the minimum supply voltage for logic circuit operating at room temperature, and higher voltages for analog circuits.

4. Minimum Channel Length and FET Speed

Under a fixed supply voltage, the reduction in channel length is limited by drain breakdown. The breakdown will occur by punch-through, tunneling or avalanche breakdown. Among these, avalanche breakdown is the most serious, since it occurs at current flowing ON-states and easily leads to permanent breakdown.

The immunity for avalanche breakdown can be measured by ionization coefficient of carriers at high electric field. The field strength to reach the same ionization coefficients for GaN is obtained as about 16 times of that for silicon and about 10 times of that for GaAs[5]. Therefore, the channel length of GaN FET can be reduced 1/16 of that for silicon FETs and 1/10 of GaAs FETs under fixed supply voltage if fabrication technologies were fully developed.

The speed of FETs is measured by the cut-off frequency. It is given by,

$$f_T = v_{SAT} / 2\pi L \quad , \qquad (4)$$

where v_{SAT} is the carrier saturation velocity and L is the channel length. The ultimate speed is compared in Table I. FETs on GaN will be the fastest due to the shortest channel length.

5. Wavelength Scaling for RF System on Chip

Fabrication cost may be one of the largest problems for high frequency millimeter wave systems. The reason is the increased accuracy requirement for passive components and their assembly, since the accuracy should be proportional to the wavelength.

If, however, the wavelength becomes small enough, every component for microwave circuit, like stub, resonator and even antenna can be integrated on a chip. There need some technological development together with proper substrate selection for millimeter operations, but the dimensional accuracy by IC technology will be sufficient for millimeter-wave components.

AlGaN/GaN HEMT with channel length of 0.1 μ m is expected to operate at 70GHz range with sufficient gain and power for short range wireless communications. The

Table I. FET speed comparison under fixed supply voltage condition.

	Si	GaAs	GaN
μ e (cm^2/Vs)	1400	8500	2000
v_{SAT} (cm/s)	1.00E+07	2.00E+07	1.25E+07
E at α=100/cm (V/cm)	1.39E+05	2.17E+05	2.28E+06
Relative speed at L_{min}	1	3.1	20.5

wavelength at 75GHz is 4mm in vacuum and around 1.3mm on dielectric substrates like GaN and sapphire. Since large diameter sapphire substrate is already available, drastic cost reduction of microwave system will be expected by monolithic integration of total RF system on sapphire with GaN FETs.

6. Conclusions

Among several miniaturization limitations, supply voltage limit due to Maxwell-Boltzmann distribution will be most imminent. Under finite supply voltages conditions, wide band gap semiconductor allows the shortest channel length resulting in the fastest device if fabrication technology is sufficiently matured.

When the channel length of AlGaN/GaN HEMT is reduced to 100nm, it can operate at millimeter-wave range with sufficient power handling capability. In addition, the wavelength is small enough to integrate passive components on chip. Monolithic integration of RF components including active transistors will alleviate the problems of interconnection, packaging and assembly for such high-frequency systems. Thus, GaN FETs on large diameter dielectric substrate will be the key technology for low-cost wireless communication system.

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