Milestones of microwave and millimeter-wave technologies —Helical Progress in Device and Circuit—

Kazuhiko Honjo^{a)}

The University of Electro-Communications

1–5–1 Chofugaoka, Chofu, Tokyo 182–8585, Japan

a) honjo@ice.uec.ac.jp

Abstract: The helical structure of progress in microwave and millimeter-wave technologies, with a focus on active device technology and circuit technology, is overviewed with some examples. The position of, and the possibilities for emerging GaN power devices and Si RF devices are described. In addition, as a new trend for methods in global analysis combining electro-magnetic waves and semiconductor devices, FDTD co-simulation is overviewed with the latest example on a 60 GHz amplifier module. Finally, the circuit technology in which the helical structure strongly dominates is overviewed. As one of endless targets for microwave circuit technology, the latest design technique for high power efficiency microwave circuits is introduced, in which co-simulation of electro-magnetic waves and semiconductor devices are effectively used.

Keywords: microwave, millimeter-wave, device, circuit

Classification: Microwave and millimeter wave devices, circuits, and systems

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1 Introduction

Recent advances in microwave devices and circuits are based on both the emerging materials and device technologies and their new design techniques in relation to more advanced CAD (Computer Added Design) technologies. Meanwhile, these microwave technologies are undoubtedly owing to the accumulated knowledge base over the span of the past century. The technological progress has often been compared to a corkscrew, where the pitch is much slower than the apparent rotating speed. In this paper, we call this structure the helical structure in technology. This paper reports perspectives on milestones in microwave and millimeter-wave technologies from the viewpoint of this helical structure.

First, emerging technologies in materials and devices viewpoints are reviewed, where GaN power devices and Si RF devices are being focused on as natural consequences of semiconductor material properties.

Second, a new trend in analysis methods for electro-magnetic waves and semiconductor devices is described. A co-simulation/concurrent design method including electromagnetic wave analysis and semiconductor device analysis based on the Finite Difference Time Domain (FDTD) method, the time domain step-by-step method, is considered essential for combinations of physical formulas such as Maxwell's equations, semiconductor equations and Schrödinger's equation. In addition, thermo-electronic coupling has become a new keyword for device and module technology.

Finally, for pursuing the ultimate goals for microwave systems, circuit technologies play very important roles. Particularly with respect to wireless systems, three measures such as high efficiency, broadband, and low distortion are eternal. Perspectives on new circuit technologies are also reviewed.

2 Emerging Technologies in Material and Device Viewpoints

During the last decade, the plan for the research and development of active microwave devices and their circuit applications has drastically changed due to the rise of the foundry service industry. Foundry services have become available not only in the field of semiconductor device fabrications, but also in the field of MEMS (Micro Electro Mechanical System) fabrications. Advanced microwave integrated circuits using devices such as InGaP/GaAs HBTs (Hetero-junction Bipolar Transistors), GaAs-based HEMTs (High E-lectron Mobility Transistors), InP-based HEMTs, 90 nm/65 nm RF Si CMOS (Complementary Metal Oxide Semiconductor Transistor) and MEMS devices can be developed without any production facilities. Thus, a rapid increase in university research activities on MMICs and LSI's has become an epoch making issue. This situation has accelerated the expansion of varieties for circuit applications.

Therefore, device research activities have tended toward breakthrough technologies such as quantum-effect nanodevices and new material-based devices. However, as far as speed is concerned, an operation principle for quantum-effect nanodevices is similar to those of classical devices such as HEMTs, and HBTs, i.e. the C-R (Capacitor-Resistor) time constants dominate the change of control voltages for these devices. This fact has caused inhibited developments of quantum-effect nanodevices in microwave and millimeter-wave ranges.

Among these situations, GaN HEMT devices and RF Si devices have attracted attention in the past five years. These two devices are categorized as an old device based on a new material, and an old device with an ultra-minute structure based on an old material, respectively.

The reason for this is clearly explained by using a semiconductor material parameter [1] table described in Table I, where Si, GaAs, InP, GaN, SiC, and diamond are compared. The energy band gap is responsible for carrier density for non-dope semiconductor substrates. Semiconductor materials with a band gap larger than 1.3 eV can be used as low tangent delta substrates for microwave transmission lines in MMIC configurations. Electron mobility,

Table I. Electric Properties for Semiconductor Materials

Material Property	Si	GaAs	InP	GaN	SiC			Diamond
					3C	4H	6H	
Energy Band Gap E _g (eV)	1.1	1.4	1.3	3.5	2.2	3.0	2.9	5.5
Electron Mobility μ (cm ² /V·sec)	1500	8500	5400	1300	650	950	420	1800
Saturation Electron Velocity v _s ($\times 10^7$ cm/sec)	1.0	2.0	2.5	2.2	2.7	2.0	2.0	2.7
Breakdown Electric Field E ₀ (MV/cm)	0.3	0.6	0.3	3.5	4.0	3.0	2.5	4.0
Relative Dielectric Constant ϵ_r	11.9	12.9	12.5	9.5	9.7	9.7	9.7	5.9
Thermal Conductivity κ (W/cm·K)	1.5	0.5	0.7	1.3	4.9	4.9	4.9	21

which is defined in the low electric field, is related to parasitic resistance and noise generation. The saturation electron velocity is one of the key parameters for microwave semiconductor materials. The values directly affect high frequency performance. The breakdown field strongly affects not only the maximum applicable voltage of the devices but also the minimum size of the devices. From the relative dielectric constant, wavelengths in the chips are determined. The thermal conductivity is especially important for power devices.

2.1 RF Si CMOS

The electron saturation velocities for these materials, which strongly affect the high frequency characteristics, are at almost the same level (around 2×10^7 cm/sec). Among them, Si has the lowest saturation velocity. However, the value is only half of that of GaAs and other compound materials. This means that a gate length shorter by one half delivers the current gain cutoff frequency, f_T , levels as the others. This fact has accelerated the development process for 90 nm gate length Si CMOS and 65 nm gate length Si CMOS, bringing about close and more than 200 GHz f_T and f_{max} . Noise figures of 0.5 dB at 10 GHz have been ready for use in the foundries. Future projections of f_{max} for 25 nm devices are expected to be 350 GHz [2], with the sacrifice of an expensive process cost due to sophisticated lithography. Due to the success of the advanced Si CMOS technology, millimeter wave MMICs and more than 40 Gbps LSIs have become the scope of Si technology.

A loss reduction for transmission lines fabricated on a Si substrate with a low tangent delta resulting from a relatively narrow band gap has been one of the major issues for Si RF circuits. The highly resistive SOI substrate for 65 nm CMOS successfully delivers 0.75 dB/mm insertion loss with the CPW structure. Wafer level packaging (WLP) technology is also a promising candidate for low loss microwave and millimeter-wave passive devices. In WLP, the dielectric material losses caused by low resistive silicon substrates, which

are suitable for very large scale integration of active devices, are avoidable without causing chip size magnification. The conductor losses can also be minimized by using an appropriate wiring metal such as copper. Figure 1 shows an example of a fabricated WLP spiral high-Q inductor [3].

Fig. 1. Spiral inductor fabricated by WLP technology [3]

2.2 GaN HEMT

Meanwhile, the breakdown electric field for GaN is one magnitude higher than the other semiconductor materials. The electric field formed with 5 V in a gap of 0.1 microns becomes 0.5 MV/cm, by which the breakdown is caused in semiconductors such as Si, GaAs, and InP. Introducing GaN to electron devices has a significant advantage in avoiding breakdown under high voltage operation. For power transistors, high voltage/low current operation brings about not only high power output but also low loss characteristics, since the loss is mainly caused both by the current and the series resistance. The main part of the series resistance comes from unavoidable circuit element matching such as bonding wires and micro-strip conductors, etc.

The most important issue for productions of GaN devices is the development of crystal growth technology based on highly reliable mass-production technologies. GaN epitaxial layers for the HEMT structure are conventionally grown on lattice matched SiC or sapphire substrates. However, there have been problems for high power device fabrications, i.e. the cost for SiC substrates is expensive and the thermal conductivity of sapphire is poor. Recently, lattice mismatched GaN on Si substrates have been developed using the AlN/GaN multilayer as a buffer layer. In this crystal system, compressive strain, which can be considered to be retained reliability, is observed using the electron backscatter diffraction technique [4].

Figure 2 compares microwave power density (solid lines) and microwave power output (broken lines) among GaN HEMT, GaAs FET, SiC MESFET, and Si LDMOS transistors at 2 GHz. In the case of GaAs FETs, the power density per 1 mm gate width is approximately 1 W/mm. Using a multi-cell, multi-chip power combining circuit technology, an amplifier output power of 250 W is obtained for GaAs FETs.

Meanwhile, a power density greater than 10 W/mm has been obtained for GaN HEMT, due to its high breakdown characteristics. Using the same kind

Fig. 2. Power output for microwave transistors at 2 GHz

of multi-chip power combining technology as the GaAs FET amplifiers, the power output for a GaN power amplifier can be estimated as 3 kW at 2 GHz. This means that the solid-state microwave oven will be realizable soon. This is one of our major microwave targets for the next 50 years.

3 A New Trend for Analysis method for the Electro-Magnetic Waves and Semiconductor Devices

Recent advances in electronic systems require complex circuit integrations with extremely high packing density in the microwave and millimeter wave frequency regions. This situation has caused serious problems not only in electro-magnetic compatibility (EMC) fields but also in accurate design for satisfying the sophisticated ultra-high frequency specifications as shown in Fig. 3. As one example, the rapid development of power amplifiers with extremely high power added efficiency (PAE) and low inter-modulation dis-

Fig. 3. A trend of analysis for electro-magnetic and semiconductor co-simulation

tortion (IMD) are needed.

For that purpose, interactions between electromagnetic waves and active components such as semiconductor crystal structures and passive components with variable shapes and complicated boundary conditions are serious problems. Moreover, design uncertainty caused by parasitic circuit elements and thermal memory effects needs to be overcome. Since the time domain analytical approach is suitable and friendly to semiconductor device analysis based on device physics equations, a time domain combination of semiconductor analysis and electro-magnetic analysis in the time domain can be considered one of the most efficient ways for a global simulation [5].

3.1 Electromagnetic Wave-Semiconductor Device Coupling

Based on the FDTD method, some successful examples of a global design technique which take into account the interactions between electromagnetic (EM) waves and semiconductor devices have been demonstrated on the microwave HBT finger length analysis [7]. Figure 4 shows a theory for co-simulation between EM analysis and a semiconductor device analysis based on the FDTD method.

Fig. 4. A principle of electro-magnetic and semiconductor co-simulation using FDTD (Finite Difference Time Domain) method

In the FDTD method, Maxwell's equations are rewritten as differential equations, and an analysis space is segmented into multiple rectangular cells. Transient electromagnetic responses are obtained by means of the time domain step-by-step calculation.

The key point of the co-simulation is a transformation of a time domain Ampere-Maxwell's equation into a time domain circuit equation (and vice versa) at the main grid edge where the semiconductor device is connected. The rectangular cell is enough small so that the electric field, $\mathbf{E}$ and the magnetic field, $\mathbf{H}$ can be treated as uniform fields. Thus, the simple line integral of $\mathbf{E}$ corresponds to the voltage, V and that of $\mathbf{H}$ corresponds to the current, I . The active device I - V characteristics obtained all from the device

simulations, the linear/non-linear circuit simulations and the measured data are acceptable for the FDTD simulations.

A typical example for the latest co-simulation is shown in Fig. 5. The example is a simulation and measurement results are for a 60 GHz amplifier module consisting of a hetero-junction FET (HFET) and planar dielectric transmission lines (PDTL) [6]. The compound device electrode structure and the electromagnetic wave-guide circuit are segmented together for the FDTD simulation as shown in the figure. The HFET has a double hetero-structure with an InGaAs channel layer. The gate size is 0.15 microns x 90 microns x 2 fingers.

Fig. 5. The FDTD Global analysis for a 60 GHz amplifier module including a pseudomorphic HEMT with compound semiconductor super lattices and the PDTL guided wave circuits [6]

I–V characteristics for the HFET intrinsic device component are simulated with the finite element method (FEM) and they are transformed into H and E in the FDTD cell. Accuracy for the device simulation was checked using on-wafer measurement for a fabricated HFET chip.

A time domain single shot excitation signal, containing frequency components from 500 MHz to 100 GHz, is applied to the module. Removing low frequency components including DC from the excitation signal is essential for reducing the calculation time. Time domain signal propagations are obtained as seen in Fig. 6. A time domain output response can be detected at an output port (Port 2). Just like tsunami wave excitation, its propagation, following to the rest, time responses for the 60-GHz amplifier module

Fig. 6. Time domain impulse propagations and their Fourier Transformation for the FDTD co-simulation [6]

have been obtained. By performing Fourier transformation both on the output time domain signal and on the excitation input time domain signal, the gain-frequency characteristics (S_{21}) can be obtained.

Measured S_{21} characteristics are also shown in Fig. 6. Although there are still some discrepancies between simulated data and measured data, the results demonstrate the potential for a global design technique in advanced millimeter-wave circuits. Not only small signal analysis, but also large signal analysis can be performed.

3.2 Thermo-Electronic Coupling

Semiconductor material parameters such as electron mobility, electron saturation velocity, even band gap energy are functions of temperature. Moreover, the density of conduction electrons and the migration of metals are also functions of the temperature. Thus, without considering operating temperature, the device and the circuit design have not been accomplished.

Comparing with the electronic phenomena, the thermal phenomena have very slow relaxation time constants. Therefore, the steady state solutions for the thermal effect have usually been used for device design. This solution is important for the reliability analysis, where a value of channel temperature divided by activation energy should be kept small to retain required mean time to failure (MTTF).

However, recent rapid advances in digital radio technology have caused

another problem: relaxation time constants (microsecond order) for the thermal response of the channel temperature in active devices are very close to modulation rates of digital wireless phone systems. The channel temperature transient causes a device parameter change that means nonlinear effects, resulting in IMD generation as shown in Fig. 7.

Fig. 7. Origin of the thermal memory effect in microwave amplifier

This mechanism is called the thermal memory effect. Estimation of the magnitude of IMD due to the thermal memory effect is one of the most important issues in modern microwave amplifier designs. For this purpose, a precise model representing the relationship between power dissipation and channel temperature is essential. Estimation of the delay and the exact value of channel temperature is a fundamental issue for understanding the thermo-electric coupling, particularly with respect to the thermal memory effect. These values depend on the physical structures concerned with thermal conduction.

Figure 8 shows a photograph and an FDTD-simulated steady state temperature distribution for an InGaP/GaAs HBT. A steep temperature gradient with distributed thermal capacitances is seen near the HBT. To model this temperature distribution with the dynamic heat capacitance, a multi-stage thermal R-C ladder network has been proposed [8]. Different from the conventional one stage R-C thermal network, the proposed 7-stage ladder network is able to represent not only the steady state temperature distribution, but also the transient phenomena of temperature responses, as shown

Fig. 8. Simulated cross-sectional temperature distribution for multi-finger HBT

(Steady state temperature distribution for the depth direction)

(Transient response for HBT channel temperature)

Fig. 9. Accurate operating temperature modeling with a 7-stage thermal R-C network

in Fig. 9.

A conventional approach using the one stage R-C thermal network is insufficient for modern microwave amplifier design. Using this new thermal model, the third order IMD can be precisely calculated as shown in Fig. 10,

Fig. 10. Accurate thermal memory effect modeling for IMD3 of a HBT amplifier

where a typical feature (the measured negative slope of IMD for a 1 kHz to 100 kHz range) due to the thermal memory effect is seen.

Not only in the IMD and the adjacent channel leakage power ratios (ACLR) for digital radio systems, but also in other electronic measures such as jitters, phase noises, EMC affairs, etc., are affected by thermo-electric coupling.

4 New Circuit Technology for Ultimate Device Performance

Advances in microwave circuit technologies have been based on a long history of helical advance, related to semiconductor circuit technology as a result of vacuum tube circuit technology. Since deriving ultimate performances of active devices is one of the major functions of the circuit technology, especially in microwave and millimeter-wave fields, a more sophisticated circuit had been required in the past to overcome the inferior performance of active devices. In this sense, the vacuum tube circuit theory is a treasure trove.

Consequently, some basic technologies have revived modern microwave circuit technology. The Doherty amplifier, the regeneration circuit based on Miller frequency division phenomena, the linear amplification using nonlinear circuit (LINC) system, the low noise matching theory, neutralization techniques for active devices, the traveling wave amplifier, the negative feedback amplifier, and the stability analysis method are good examples. These technologies have appeared helically with appropriate modifications to develop higher frequency applications in our microwave society (e.g. Si bipolar transistor hybrid integrated circuits (HICs) in the 1970s, monolithic microwave integrated circuits (GaAs FET MMICs) in the 1980s, HBT and HEMT MMICs in the 1990s, and GaN HEMT HICs, MMICs and Si RFICs in 2000s.

From the viewpoint of wireless communication applications, an ultimate target of research and development for wireless device technology is pursuing ultra-high power efficiency, ultra-wide band characteristics with extremely low distortion characteristics. Pursuing 100% power efficiency is an endless objective, though operation frequency is always increasing.

A basic principle in achieving high power efficiency is to avoid the overlapping of current and voltage waveforms at transistor terminals. There are time domain approaches with switching circuits and frequency domain approaches with impedance modification for this objective.

Our long, helical history clearly states that frequency domain approaches are always at the forefront of higher frequency development, since accurate measurement equipment such as network analyzers in the frequency domain is always keeping a superior position against time domain measurement equipment such as oscilloscopes, though in the end all of the devices are replaced by time domain digital devices.

One of the frequency domain approaches for this final goal is that the transistor load impedances are set to be open for odd-order higher harmonic frequencies, while retaining a power factor of minus unity for a fundamental frequency. Note that all parasitic elements around a transistor current source

have to be canceled. This method is called the class-F amplifier [9]. The principle of this method is old and simple.

Fourier analysis demonstrates the relationships between the highest order of voltage and current waveforms and power efficiency as shown in Table II. The most important issue for the class-F amplifier at present is to develop a higher frequency range with state of the art technology for circuits and devices. In most cases, treated higher harmonic frequencies are up to 3rd order harmonic frequency. These cases mean that the theoretical upper limit for PAE is automatically restricted below 81.7% according to our data. To overcome this issue, considerations of both active and passive devices are necessary.

Table II. Power efficiency vs. treated harmonic frequency based on Fourier analysis

		Voltage Waveform Components			
		← Odd Order →			
Current Waveform Components ↑ Even Order ↓		f_0	$3f_0$	$5f_0$	∞
	f_0	50 % (Class A)	57.7 %	60.3 %	63.7 %
	$2f_0$	70.7 % (Practical Class B)	81.7 %	85.3 %	90.3 %
	$4f_0$	75.0 %	86.6 %	90.5 %	95.5 %
	∞	78.5 (Ideal Class B)	90.7 %	94.8 %	100 % (Ideal Class F)

The active devices have to possess sufficient power gain even at the highest order of harmonic frequency. A frequency region with maximum stable power gain (MSG) is suitable for harmonic frequency treatments, where K factor is less than unity. To confirm sufficient power gain for the class-F amplifier, the conversion point frequency, f_{con} , from MSG to MAG (maximum available power gain) has been verified for an AlGa_N/Ga_N HEMT chip by using previously mentioned FDTD co-simulation [11].

As seen in Fig. 11, a sufficient power gain ($f_{\text{con}} = 18$ GHz) was observed for a gate finger length less than 100 microns for 1.9 GHz band class-F amplifiers. After that, a set of large signal parameters for an AlGa_N/Ga_N HEMT chip has been extracted using an on-wafer measurement system. DC characteristics have been measured and modeled under a long bias pulse condition so that the simulated device temperature can be set as the operating device channel temperature [11].

From the perspective of circuit technology, increasing the harmonic treatment number without introducing any losses is one of the major concerns. Figure 12 shows a distributed circuit configuration for a class-F amplifier applicable to the arbitrary-higher-order harmonic frequency treatment [10].

Fig. 11. FDTD co-simulated and measured characteristics of GaN HEMT

Fig. 12. Distributed circuit Class F amplifier configuration applicable to arbitrary-higher-order harmonic frequency treatment [10].

Lumped element circuit approaches for the arbitrary order treatment have also been reported for class-F and inverse class-F amplifier circuits [13].

Canceling the parasitic elements around the transistor is still a difficult problem to address. Figure 13 summarizes the state of the art performance for high efficiency amplifiers that appeared in IEEE and IEICE publications. In this figure, not only class-F amplifiers, but also other types of amplifiers such as class-D, class-E, harmonic controlled amplifiers, etc., are plotted. Since transistor parasitic elements cause very low reactance at low frequency ranges, the problem of parasitic element cancellation matters little. Thus, at 10 MHz, more than 90% PAE has been obtained. Our present final goal is arranging for similar circumstances in microwave and millimeter-wave ranges to achieve 90% efficiency. By the time microwaves and millimeter-waves can be treated the same as DC, more than 90% power efficiency will be

Fig. 13. State of the art performance for high-efficiency amplifiers

achieved easily in microwave and millimeter-wave ranges. At the same time, digital signal processing type high-efficiency amplifiers will prevail and we will also begin the development of class-F amplifiers in THz frequency regions, according to the helical structure of progress.

5 Conclusion

The helical structure of progress in microwave and millimeter-wave technologies focusing on active device technology and circuit technology were overviewed with some examples. Since the technological progress has often been compared to a corkscrew, where the pitch is much slower than the apparent rotating speed, we can find a lot of ideas in the past research results over the span of century. We have to add something specials to our knowledge base under the helical structure of progress. Emerging GaN power devices has been based on accumulated both crystal growth technology and device/circuit design technology. Also Si RF devices have been owing to advanced minute processing technology and their circuit modifications. The FDTD modifications of Maxwell's equations have opened up the global analysis method including the electro-magnetic waves and the semiconductor materials. The circuit application field is strongly affected by the helical structure. Due to limited number of pages, examples and technology fields introduced in this paper are limited. There are a lot of the other good examples.

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Kazuhiko Honjo

received the B.E. degree from the University of Electro-Communications, Tokyo, Japan, in 1974, and the M.E. and D.E. degrees in electronic engineering from the Tokyo Institute of Technology, Tokyo, Japan, in 1976 and 1983, respectively. In 1976, he joined Central Research Laboratories, NEC Corporation, Kawasaki, Japan. In 2001, he moved to the University of Electro-Communications, where he is currently a Professor with the Department of Information and Communication Engineering. He

has been involved in research and development of high-power/broadband/low-distortion microwave amplifiers, MMIC's, HBT device and processing technology, miniature broadband microwave antennas and FDTD electro-magnetic wave and device co-simulation. Prof. Honjo was the recipient both of the 1983 Microwave Prize and the 1988 Microwave Prize granted by the IEEE Microwave Theory and Techniques Society (IEEE MTT-S), the 1980 Young Engineer Award, and the 1999 Society Award (Electronics Award) both presented by the Institute of Electrical, Information and Communication Engineers (IEICE), Japan. He is Fellow both of IEEE and IEICE.