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Trends in Research and Development on Next-Generation Devices (from IEEE IEDM)

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4.1 Introduction

The IEEE IEDM (International Electron Devices Meeting) was held in Washington DC, the United States, from December 2 through December 5, 2001. This meeting is known as one of the most authoritative meetings that serve as opportunities for presenting achievements of research into leading-edge technologies.

Each year, the latest achievements are presented at the meeting, including presentations on silicon MOS devices, which have increasingly been downsized, single-electron transistors (SETs), and carbon nanotube devices (also referred to as CNTs: carbon nano-tube transistors).

The number of attendants drastically decreased in 2001 due to the September 11 terrorist attacks and the IT slump (according to the organizer, the number dropped from approx. 2,000 in 2000 to 900 in 2001). However, there was a hot atmosphere in the venue since much greater achievements than had been previously expected were made in many fields including a presentation by IBM on a carbon nano-tube transistor, which indicated the device's higher feasibility and scalability than that of Si elements, and Fujitsu's presentation on an SOI MOS transistor that achieved the high level of RF property, which had been estimated to be achievable in around 2016 on the roadmap.

Concerning the participating nations, this year's meeting was characteristic in that European and Asian countries gained power in addition to the existing US-Japan bipolar structure. From Europe, even those nations having relatively small economic scales (e.g., Greece and Iceland) participated in the meeting by responding to research into leading-edge devices, which require huge investments, through multinational alliances. It can be said that efforts are being made by the EU as a whole to grapple with research into leading-edge devices.

In Asia, it is notable that South Korea and Taiwan, which are specialized in memory devices and liquid crystal devices, are expanding their spheres of research to basic areas, such as quantum devices, in addition to application products.

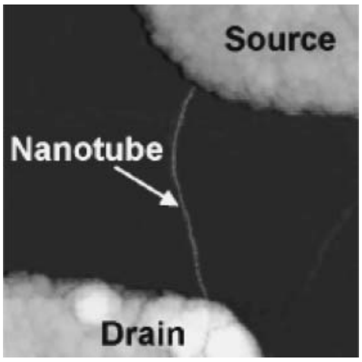
As courses of direction in research and development, it was noticeable that unlike that of Japan, particular focus was placed on the development of high dielectric-strength transistors (in Japan, development of GaN-based devices is focused on short-wave luminescent elements such as blue LED and laser), Si-Ge transistors and MEMS (micro electro mechanical systems).

Concerning MEMS, bio-MEMS and microfluidics discussion sessions were given separate timeframes from other sessions. Thus, it can be said that the IEEE Electron Device Society is particularly interested in these interdisciplinary areas.

Semiconductor device technologies are one of the technologies for which Japan has maintained a very high level in terms of international competitiveness. However, given that European and Asian nations are rapidly gaining power and pressing hard on Japan also in those fields close to basic research, it is necessary for Japan to establish focus areas of research and devise strategies from a comprehensive point of view as a country.

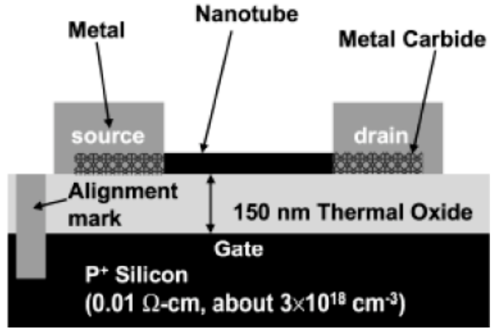
Japan has ceded its top position in production volume to South Korea in the fields of DRAMs and liquid crystal devices, where Japan used to have overwhelming power. Taiwan, which has emerged as a foundry for US companies, is building up

Figure 1: Carbon nanotube transistor



(Interval between the source and drain electrodes is 1 μm.)

Figure 2: Structure of the carbon nanotube transistor



leading-edge technologies and know-how on process technologies Thus, it is becoming extremely difficult for Japan to maintain its top position.

With regard to approaches toward research and development investments, borderless, large-scale investments are increasing, such as basic research by European countries that have formed alliance within the EU circles, sharing of design and process technologies between US manufacturers and Taiwanese foundries, and a joint venture in liquid crystals between Philips of the Netherlands and LG of South Korea.

With regard also to cooperation between academic, business and governmental sectors, the approaches taken in the US and Europe appear to be advancing more than Japan in terms of distribution of participating institutions.

This report will explain the research achievements in leading-edge devices presented at the IEEE IEDM, and examine the current problems and future challenges through comparison of research activities between the United States, Europe and Asian countries while identifying the position of Japan amid the global trend in research and development of advanced devices.

Table 1: Comparison between CNFET (presented at this meeting) and Si-MOS

	p-CNFET	100nm MOSFET	25nm MOSFET
Transconductance (μS/μm)	122	1000 (nFET) 460 (pFET)	1200 (nFET) 640 (pFET)
External resistance (Ω-cm per side)	< 70	~ 66 (nFET) ~ 143 (pFET)	~ 40 (nFET) ~ 86 (pFET)
Gate insulator(nm)	150	2.0	0.8

4.2 Presentation that attracted much attention

This section introduces those research achievements that attracted much attention at the meeting (the following figures are all excerpts from the collection of documents prepared for the IEEE IEDM).

1) Carbon Nanotube Transistor (CNFET)

This transistor was presented by the IBM Watson Lab. The presentation was made as part of the Nanoelectronic Devices session, which also contained a presentation for SET (single electron transistor). Nevertheless, although only half of the venue's seats was filled in the first part of the session, there were even standees just before the CNFET presentation started. Thus, the presentation was one of the hottest ones at this year's IEDM.

The main feature of the presentation demonstrated that the new device showed a high level of performance comparable to Si-MOS through improvements on the electrode structures of a series of the carbon nanotube transistors presented in 2001, and that the new device can be upgraded through down-scaling (i.e., miniaturization) as with Si-MOS.

As shown in Table 1, the carbon nanotube transistor's transconductance — factor that represents the performance of a transistor — is smaller than that of the Si-MOS. The reason is because the gate length is 1 μm greater than and the gate oxide film is 150 nm longer the Si-MOS transistor. It is estimated that with the gate length at 100 nm, performance of 1,257 μS/μm can be achieved, and at 25 nm, 5,028 μS/μm can be achieved.

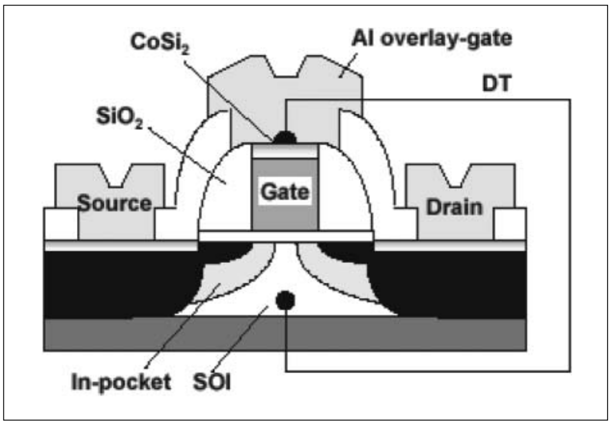
It was also impressive that the presenter mentioned Dr. Iijima of Japan as the discoverer and inventor of the carbon nanotube, thus correctly acknowledging the origin of their research.

2) SOI Transistor

Fujitsu Laboratories of Japan presented a Si-MOS whose fmax (maximum oscillation frequency) reaches 185 GHz (double the present value). In addition, this device's noise level is as low as that of AlGaAs/GaAs HEMT (i.e., 0.8 dB at 10 GHz).

The device is also characteristic in that it has the SOI (silicon on insulator) structure, as indicated in Figure 3, and the DT (dynamic threshold) structure where the gate electrode is connected to the body.

Figure 3: Structure of DTMOS



Thanks to this achievement, the high level of RF property, which had been estimated to be reachable around 2016 on the research and development roadmap of ITRS, was realized in 2001.

It is enormously significant that Si-MOS transistors, which can be densely integrated at low power consumption and are highly cost effective, may be used also in the RF area, which was previously achieved only with expensive compound semiconductors or high power-consumption Si bipolar transistors.

3) High Dielectric-strength GaN HEMT

The presentation was on a joint research project between UCSB (University of California Santa Barbara) and Yale University. The device is designed to gain a high dielectric strength by forming a SiO_2 layer immediately beneath the gate in the AlGaN/GaN-based HEMT structure and having electrons trapped by a charge generated from the SiO_2, thus to suppress the leak when the circuit is turned off.

The device demonstrates higher performance than preceding SiC-based devices, in terms of both dielectric strength and on-resistance.

It has a dielectric strength of 1,300V and an on-resistance of 1.7 $m\Omega/cm^2$.

Of dielectric-strength transistors, GaN-based transistors are the most advantageous in terms of

Figure 4: Comparison of roadmaps with ITRS

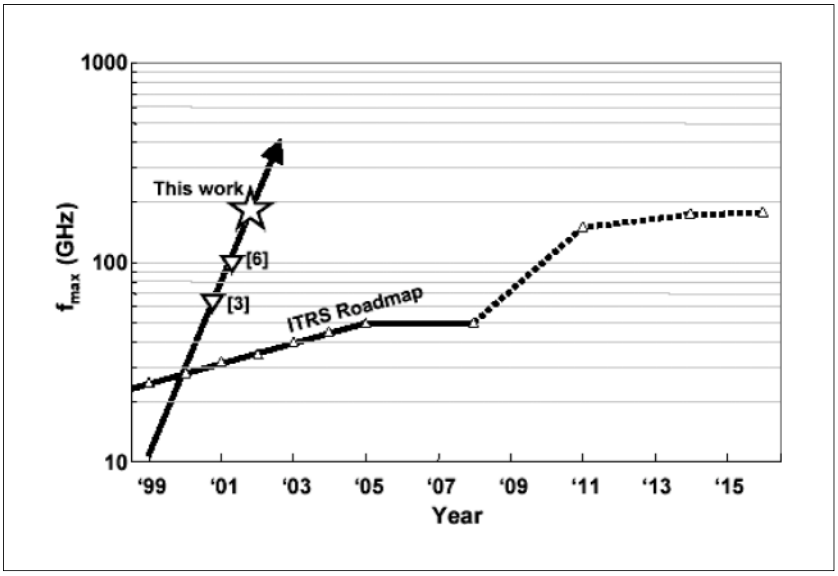


Figure 5: Structure of the high dielectric-strength HEMT

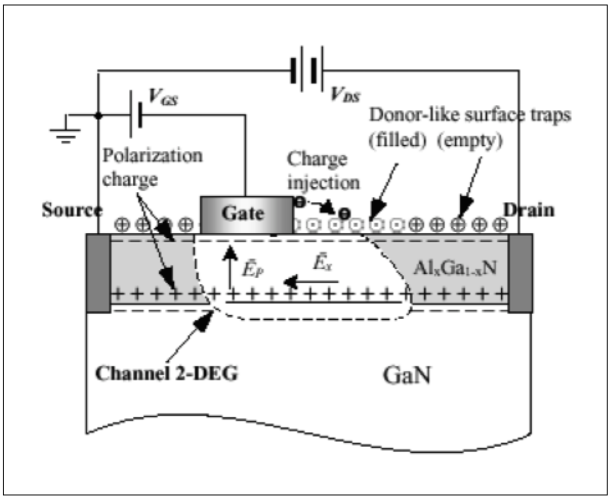


Figure 6: Pattern diagram of the operating principle

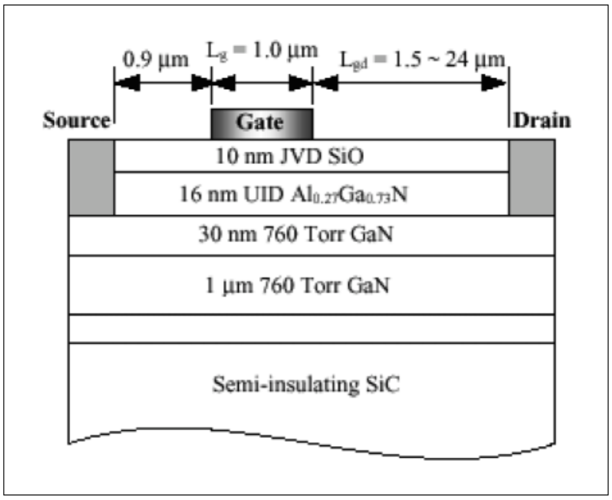
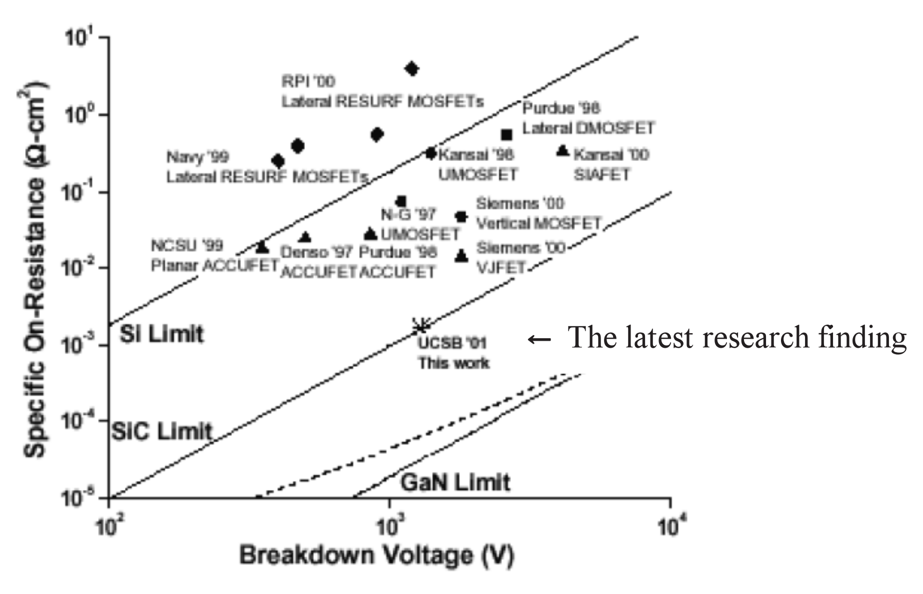


Figure 7: Comparison between GaN-, Si- and SiC-based devices



the physical properties of the material. In Japan, however, GaN research is mostly in the form of luminescent devices such as laser diodes and LEDs, rather than as a material of transistors.

4.3 Trends in research and development by country

This section will analyze the presentations at this year's IEDM from a sci-tech, political point of view. Table 2 shows a list of countries to which the research papers or reports presented at IEDM belong. The total number of the papers and lectures in the parentheses includes the number of keynote lecturers, but excludes panel discussion participants.

In the ranking in terms of the number of papers on research into leading-edge devices, the United States, Japan, South Korea, Taiwan and Germany represent the top 5 countries, respectively. Thus, the rankings are closely linked with the positions of those countries in the current world market for semiconductor devices. Additionally, this table indicates considerably high levels of technologies in 3 European countries: Belgium, where IMEC serves as the base for jointly developing semiconductors used in Europe; France, where institutions including state-run communication carrier Alcatel have gained top-class achievements in the development of communication devices; and the Netherlands, where Philips and other organizations have conducted a wide array of research projects ranging from basic technologies, including simulation and process technologies, to

Table 2: Number of Research Papers by Country

Ranking	Name of country	No. of papers
1	USA	97
2	Japan	56
3	Korea	19
4	Taiwan	13
5	Germany	11
6	Belgium	7
7	France	5
8	Netherlands	5
9	China (Hong Kong)	3
10	Spain	2
11	Singapore	2
12	Switzerland	2
13	Finland	1
14	Canada	1
15	Ireland	1
16	Greece	1
17	Argentina	1

Total number of papers and lectures: 216, inc. overlaps through joint research projects

high-frequency devices.

It is also notable that China (Hong Kong) provided three presentations. They consisted of one project conducted by China individually, and two research projects that were jointly conducted with Singapore and the United States. The next section analyzes these joint research forms in detail. These data are an important factor in analyzing the forms of research in those previously low-profile countries doing research on advanced devices, such as Spain, Ireland, Greece, and Argentina.

4.4 Forms of research and development

This section analyzes specific forms of research and development. Table 3 represents a table of institutions to which the presenters belong, categorized into Japan, the United States, Europe, Asia and other areas, and classified into business, academic and governmental institutions.

This table indicates that the number of presented research projects by academic and governmental organizations in Japan is very small for leading-edge devices. Furthermore, by analyzing the table together with Table 2, you can identify the status quo of joint research projects by country and by region (the number of overlaps represents the number of collaborations) and that there are fewer collaborations between business, academic and governmental institutions in Japan compared to other countries.

Table 3: Numbers of business, academic and governmental Institutions by region

Region	Business	Academic	Governmental
USA	63	45	4
Japan	49	7	0
Europe	24	11	16
Asia	27	14	6
Others	1	2	0

Total number of papers and lectures: 216, inc. overlaps through joint research projects

Research on leading-edge devices has reached the nano level, and quantum effects can no longer be disregarded. Thus, even engineers are increasingly required to have higher levels of physical and quantum-mechanical backgrounds in this area. It will be also essential to form collaborations with universities in order to fortify these physical foundations. In Japan, however, it appears that business-academic collaborations like those found in the US, Europe and other Asian countries are barely functioning as far as the present state is concerned. If IT and nano technologies are positioned as the next-generation pillar of Japan as an established technology-oriented nation, acute measures are urgently required.

Multinational joint research projects by region are analyzed as follows. Of the 216 presentations, research papers prepared across two or more nations accounted for 19. Of the 19 projects, multinational collaborations involving Japan represented only 2 (research projects by local affiliates are counted as research projects of the respective nations). Table 4 shows these data in a table.

In addition to the strength of joint research within the European region, those coalitions such as the US-EU alliance are also notable. The United States and EU announced an alliance in the field of nano technology in January. This can be considered an example of such a coalition.

Table 4: Number of multinational collaborations

Region	No. of collaborations
Europe - Europe	6
USA - Europe	4
USA - Asia	4
Asia - Asia	1
USA - Japan	1
USA - Europe - Asia	1
USA - Europe - Japan	1
USA - Europe - Others	1

In many cases, research on leading-edge devices requires a huge amount of capital investment such as research into semiconductor devices. In a sense, Japan has the potential to independently make huge capital investments or research investments, and therefore it is not appropriate to negatively regard all factors. However, it will also be necessary to promote coalitions with other nations from the viewpoint of improving investment efficiency and efficient management of intellectual properties.

Japan needs to consider the best form of research for efficiently forming multinational coalitions and efficiently demonstrating its leadership.

As a trend identified through more in-depth analysis of the data, it is indicated that Japan has fewer joint-research projects not only among business, academic and governmental institutions, but also among private companies as a group, and among universities as a group. This is another cause of concern.

In the United States, joint research projects between top-class universities are commonly conducted, such as those between MIT and Stanford University, and those between Yale University and the University of California Santa Barbara. On the contrary, in Japan, joint research projects such as collaborations between Tokyo University and Kyoto University are rare. In fact, there are only a small number of business-academic and inter-university coalitions in Japan. This is one of the problems to be tackled since it may also concern human resource demography including personnel affairs between universities.

4.5 Details of research areas

As a result of detailed analysis of research areas, it was learned that of the 7 presentations in the "DRAM Technologies" session, Japan represented 2, the United States 2, South Korea 2, and Germany 1. However, in the more theoretical "Scaling Trends of Advanced Devices" session, the US represented all the 5 presentations. And, in the "Device Simulation" session, the US represented 2, Japan 1 and Germany 1. Thus, the relative position of Japan was lowered.

Concerning the "Bio MEMS and Microfluidics" session, a separately organized event that attracted much attention, of the 5 presentations, the US represented 2, Germany 1, Singapore 1, and Greece 1. Japan provided no presentation in this session.

Although Japan is taking the lead in some of the basic areas such as with SET (single electron transistor), it can be said that our country is weak in the fields of theory building, such as device theories and simulations, and in the fields of interdisciplinary research such as bio-MEMS and microfluidics. This is yet another major problem.

4.6 Conclusion

The IEDM held in December demonstrated achievements of research into leading-edge devices that are suitable for the opening of the 21st century. In particular, it is greatly significant that with feasible support, the event showed the world of electronics that are not on an extension of the present times, such as carbon nanotube transistors, which will open up the nano-electronics world.

The Japanese research findings presented at the IEDM also deserve appraisal since they included top class achievements in the development of the Si-Ge-based high-speed transistor, which had been considered to be lagging behind, and that the realization schedule for SOI devices on the research roadmap was quickened by more than 10 years. Since Japan was acknowledged as the origin of the carbon nanotube, whose presentation gained the highest level of attention at the meeting, and acquired high acclaims also for its research efforts in those fields very close to basic research, such as research on single electron transistors, it can be said that those presentations fully demonstrated Japan's true abilities.

However, it is also an obvious fact that to some extent Japan has become alienated from the global trends in both form and method of research. Although all the international trends are not necessarily correct, Japan must establish a structure to further accelerate business, academic and governmental coalitions despite the fact that Japan is already encouraging those collaborations in accordance with promotional policies and the likes.

Following the IEDM, we had a discussion with professors and students at Yale University. There was an interesting opinion in the discussion. The opinion was concerning Japan's and the United States' setting of research goals. It was pointed out that in Japan, most goals are set in the "buildup" style where the development of a new device comes first and then a future society using the device is predicted, while in the Unites States, goals are mostly set in the "break down" style in which the form of an ideal computer, for example, is determined first, then a device(s) required for the computer is/are designed.

Concerning the latest IEDM, it also suggested that unlike Japanese approaches toward research and development, aggressive approaches were taken in the development of the GaN transistor or the development of LEDs for short-distance data transfer in the States because these approaches were based on that kind of goals.

The idea by NNI (National Nanotechnology Initiative) in the US of developing a cube sugar size computer capable of storing the entire collection of books held by the National Library is also based on the same goals. It is not a figurative expression that a computer will have such an enormous capacity as a result of progress by various devices. The technology required to achieve that capability is not on an extension of the existing technologies, and discontinuous dots are inevitably required in drawing the line reaching the goal. This is an innovative breakthrough that can be clarified only by setting a high level of goals.

There are many criticisms concerning the goal of a basic plan that aims at establishing a research base for science and technology on which Japan can produce 30 Nobel Laureates in 50 years. However, the intension is not to count the Laureates every year and make an evaluation based on the number. With an extension of the conventional structure, our Nobel Laureates will not reach 30 in 50 years. The goal has been set on the grounds that it can be achieved only when the environment surrounding science and technology in Japan, including research bases, research forms, personnel training, and even intellectual creation and amalgamation, is established in a near ideal form.

Arguments are expected from the viewpoint of what the research bases, research forms, personnel training and intellectual creation for achieving this goal should be, and how the discontinuous dots lying on the process toward the goal should be connected for a breakthrough.

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