Technology Transfer of High Frequency Devices for Consumer Electronics

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Abstract—**The aspects of high volume production on the order of millions of devices per month for consumer electronics are different from those for small and medium scale production and high-end telecommunication, instrumentation or military applications. The keys to technology transfer are also different. By investigating the examples of successful technology transfer of high frequency devices at Sony, these issues will be illustrated. The author's opinion regarding some future applications of high frequency devices in consumer electronics will also be presented. Then, a proposal for global industrial collaboration to bring these products to a sufficient level of maturity for widespread use is made.**

Introduction

HIGH frequency devices have always been the key to opening new markets in consumer electronics. However, they have also been difficult to manage both in R&D and during transfer to mass production. At the same time, it is widely understood that the consumer market can provide a strong driving force for industry and technology, as we have recently seen in satellite broadcast applications. What is unique about consumer electronics are the size of production and the cost concerns. The huge production volume of consumer electronics will usually justify extensive technology investment even though a great risk is associated with it. Cost is a great concern because the product must be priced as low as consumers would think reasonable.

Significant high volume applications of high frequency devices for consumer electronics are now expected in the DBS (direct broadcast satellite) receiver and cellular telephone markets. DBS systems utilize the high frequency microwave range around 12 GHz, and cellular telephones, lower frequencies around 1–2 GHz.

Although the high frequency performance of solid state devices has improved rapidly, vast microwave and millimeter wave frequency bands are not yet developed for consumer use. Future technology advances will open up even the usage of the Terahertz range.

Also, the world can expect new high frequency engineering resources due to the relaxation of the military tension which has existed between two major powers. It would be desirable if the resources previously allocated for development of military systems could be utilized for the creation of markets in consumer electronics.

This paper will discuss some past examples where Sony transferred technology from industrial or military domain to the consumer electronics. This history allows an enumeration of the key factors for successful transfer.

The paper concludes with projections of some future applications of high frequency devices in consumer electronics. Lastly, a proposal for global industrial collaboration to accomplish this is made.

Manuscript received July 10, 1992; revised July 30, 1992.

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IEEE Log Number 9203715.

I. Historical Cases Where High Frequency Devices were Applied to Consumer Electronics

Historical cases will be presented for investigating the key issues in transferring high frequency technology to mass production for consumer applications.

A. Transistor Radio, Tunneling Diode

In 1952, the AM radio frequency range from 500 kHz to 1600 kHz was considered to be "high frequency" for early transistors which only had found limited use in hearing aids and instrumentation.

M. Ibuka, founder of Sony, decided to apply this technology to radios. Even though the yield was as low as five percent, he directed the company to begin mass production [1]. Two years of intensive work ranging from crystal growth to device fabrication resulted in a dramatic improvement of the transistor's high frequency performance. In 1955, Japan's first transistor radio was launched based on this development. Fig. 1 shows the picture of the early transistors and the first transistor radio commercialized by Sony.

Later when silicon transistors came out and were being introduced into military applications, Mr. Ibuka again risked the company to develop a transistorized television for which germanium transistors were not suitable. Again by intensive work, the company was successful in launching the world's first transistorized television in 1959.

This success truly opened up the age of the analog semiconductor industry [2].

There was another aspect of success. While concentrating on the transistor, Mr. Ibuka asked electronics parts manufacturers to develop new miniaturized components to make radios and televisions really small. The "bar antenna" made of a ferrite bar wound by a few turns of coils

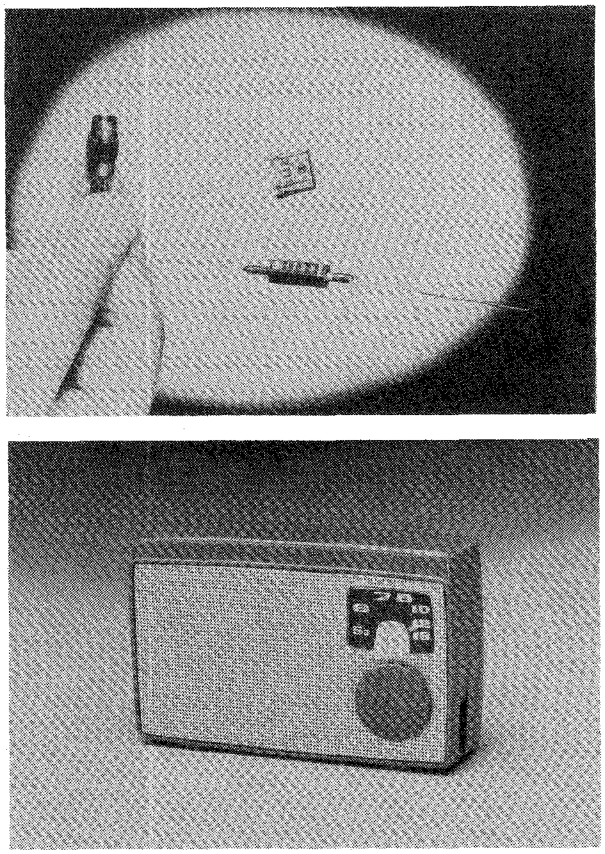

Fig. 1. Photograph of the early transistors and the first transistor radio commercialized by Sony.

1947	Invention of Transistor at Bell Labs
1952	Sony Contacted with Western Electric
1953.10	W.E. and Sony Signed Contract of Patent License
1954.2	Japanese Goverment Permission
1955.8	Janan's First Transistor Radio (TR-55)
1956	Nobel Prize to W. Schockley, J. Bardeen and W. H. Brattin
1956	World's First Transistorized Tape Recorder
1957	Tunneling Diode (L. Esaki)
1959	World's First Transistorized TV Using Silicon Transistors
1965	World's First Transistorized Video Tape Recorder
1968	World's First Transistorized Color TV

Fig. 2. The history of the transistor and Its applications at Sony.

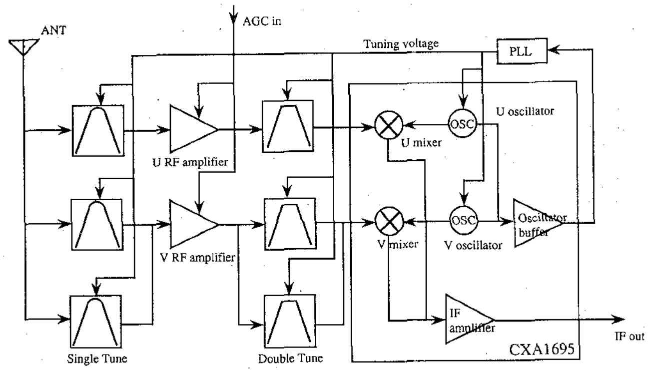

Fig. 3. Functional block diagram of VHF/UHF tuner IC.

was an example which made the antenna very small. The "polymer-varicon" was another example where plastic film as dielectric layer greatly reduced the size of the variable condenser. All of these efforts were based on the strong motivation to realize very small electronic products which truly touched the heart of the public because they then could enjoy entertainment and information everywhere. This policy has been pursued in later products developed at Sony.

In the effort to pursue high frequency performance, the tunneling diode [3] was invented in 1957 by L. Esaki, who was then a researcher at Sony. All of the effort to commercialize the device for consumer applications failed due to difficult circuit design. However, he was awarded the Nobel Prize in 1973 for the discovery.

The history of the transistor and its applications at Sony are listed in Fig. 2.

B. Tuner ICs and Radio ICs

In the early 1970's, silicon monolithic ICs could not cover the VHF and UHF range for televisions. Starting in 1974, the author and his group launched the development of mixer-oscillator ICs for VHF and UHF TV tuners [4]. The shallow junction technique which was until then applied only to a very limited microwave transistors was first employed for consumer applications.

The development of tuner ICs was part of the effort to launch televisions incorporated with electronic tuners [4]. This allowed TV tuner design in which for the first time components including varactor diodes and tuner ICs were mounted on a printed circuit board elminating mechanical contacts. Electronic tuners opened the way to intelligent televisions which provide a number of functions such as programmed video-recording.

Design for efficient production was pursued as well as cost reduction to meet the requirement for the market. Despite the sophisticated semiconductor technology in both tuner ICs and varactor diodes, their cost was reduced to a level comparable to that of other parts of that time.

Fig. 3 illustrates the functional block diagram of VHF/UHF tuner IC. The front-end amplifier was not integrated, leaving flexibility for any technical advancement to come later. The history of tuner ICs is listed in Fig. 4. It can be seen that the frequency coverage has been expanded, and the production quantity reaches 15 million pieces annually at Sony alone.

The radio IC was also a challenge because a number of functions including filters which monolithic ICs found difficult to handle had to be integrated. Two radio design engineers were enthusiastic to work within the semiconductor design and processing facilities for a couple of years in order to fully utilize the capability of the monolithic structure. Finally they realized one-chip radio ICs [5]. Fig. 5 illustrates the functional block diagram of radio IC. These ICs enabled Sony to launch card sized radios which became a major product line and revitalized the radio industry.

The history of radio ICs is listed in Fig. 6. The production volume of 200 million pieces per year at Sony shows that these enormous efforts have paid off well.

Model	Year of Introduction	Operating Frequency	Application	Production Volume/year
CX097	1974	47~222MHz	VHF TV Tuner	15million pcs
CX099	1978	47~222MHz	VHF TV Electronic Tuner	
CXA1125	1986	47~470MHz	CATV/VHF TV Tuner	
CXA1355	1990	47~890MHz	UHF/CATV/VHF TV Tuner	

Fig. 4. History of Sony Tuner ICs

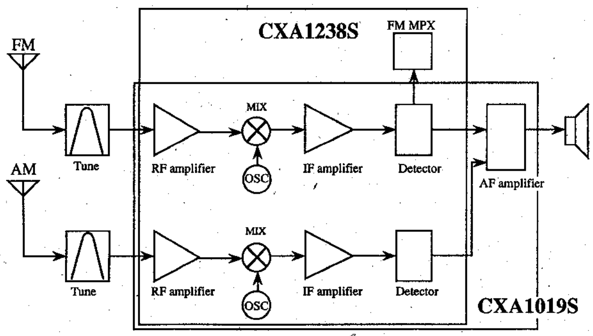

Fig. 5. Functional block diagram of radio IC.

Model	Year of Introduction	Application	Production Volume/year
CX845	1982	1 chip AM Radio	200 million pcs
CX20029	1985	1 chip AM/FM Stereo Radio	
CXA1032	1986	1 chip AM Card Radio (Low power consumption)	
CXA1600	1992	1 chip AM Card Radio (Needs few devices outside)	

Fig. 6. History of Sony Radio ICs.

The photograph of tuner ICs and one-chip radio ICs are shown in Fig. 7. Packaging has been of crucial concern because it has to satisfy both high frequency performance and low cost requirement. After extensive chip design efforts, the standard packages were successfully employed.

C. GaAs MOCVD (Metal Organic Chemical Vapor Deposition)

Back in 1970's, research on MOCVD was started at Sony Research Center, motivated by the high productivity associated with the high crystal quality obtained through chemical process. In the early 1980s, laser diodes were made by liquid phase epitaxy [6], and MBE (molecular beam epitaxy) was projected for HEMTs [7]. Both of them are intended for communication systems. The author and the group of N. Watanabe decided to apply MOCVD to both laser diodes and HEMTs [8]–[11]. Fortunately, they were the first to deliver mass-produced HEMTs. These almost instantly replaced the front-end devices for direct broadcasting satellite receivers. They were also successful in first applying MOCVD to mass-production of laser diodes. As is seen in Fig. 8, today more than 50 million

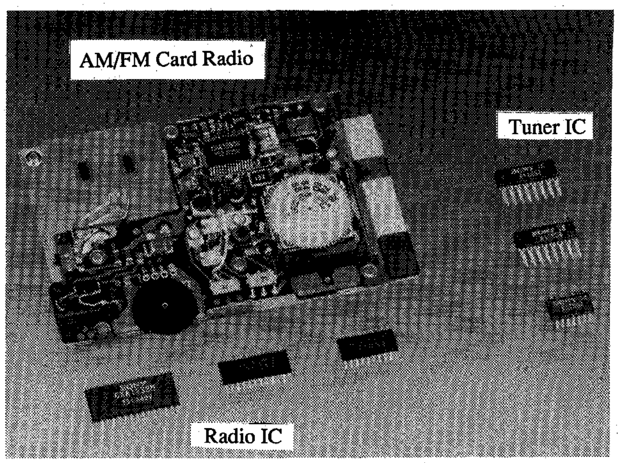

Fig. 7. Photograph of tuner ICs and one-chip radio ICs and one-chip radio ICs.

	Applications	Production Quantity (pieces in 1991)
HEMTs	DBS Receiver	50,000K
Laser Diodes 780 nm	Compact Disc	
Laser Diodes 670 nm	Pointer	600K
Laser Diodes 10 mW- 3 W	MO-disc Surgery	

Fig. 8. High speed and optical devices made by MOCVD at Sony.

pieces of laser diodes and HEMTs are produced annually at Sony.

The high productivity of MOCVD together with an efficient assembly process enabled the transfer of laser dioides and HEMTs from the communication domain to the consumers. The cost effectiveness enhanced the market build-up for compact discs [12] and DBS receivers [13].

II. Key Factors for Successful Transfer

From the above examples, a few key factors for successful transfer of high frequency devices to mass production for consumer markets will be summarized.

1) Original, creative designs for heart-touching products are most important in consumer electronics such as transistor radios and televisions. The creativity should be demonstrated not only in technologicial research but also in marketing and product planning [14].
2) A number of managerial innovations and efforts are important. They are:
   Clear target setting and commitment by top management.
   Appointment of a strongly motivated project manager.
   Concentration on selected key technologies along with collaboration on other subjects to complete truly innovative development.

Transfer of key R&D personnel to production and marketing.

3) Establishment of a cost competitive production environment including suppliers dedicated to continuous improvements in cost, quality and productivity.

III. Projections of Future High Frequency Consumer Applications

From the author's viewpoint, four high frequency technology fields look interesting for consumer applications.

1) Personnal communication terminals and devices for them.
2) An up-conversion tuner for tuning all the signal channels below UHF.
3) An active phased array antenna for multiple satellite receptions.
4) Millimeter wave devices and systems.

A. Personal Telecommunications

Personal telecommunication terminals will become typical consumer products in the near future using frequencies in the 1 to 2 GHz range. An example of a circuit configuration for the high frequency part used in handset terminals is shown in Fig. 9. An example of system partitioning into monolithic ICs is listed in Table I. The circuit functions enclosed by dotted boxes in Fig. 9 represent prototype models using GaAs Junction FET technology [15]. Appropriate system partitioning is a great concern because it strongly affects the manufacturing cost and the designer-friendliness.

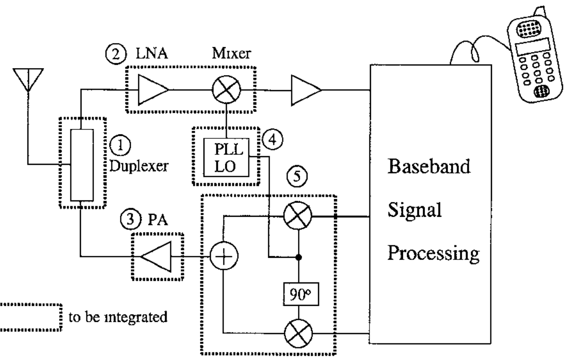

Fig. 9 Functional block diagram of Digital Personal Communication Terminal.

TABLE I
High Frequency Devices for Personal Communication Terminals (Prototype JFET ICs by Sony)

① Antenna Duplexer
② Front-end IC (LNA & Mixer)
③ Power Amplifier (Linear/Saturated)
④ Synthesized Local Oscillator
⑤ Quadruture Modulator

B. Up-Conversion Tuner

The up-conversion tuner which employs a microwave frequency as the intermediate frequency stage has been studied for a long time. Its applications have been quite limited so far but should be reconsidered now because of the recent progress of high frequency devices.

A functional block diagram of the up-conversion tuner is shown in Fig. 10. Technologies for realizing an up-conversion tuner covering a sufficiently wide range of frequencies are listed in Table II. It is clear that a number of technical challenges still remain. A wide range tracking filter with very low insertion loss will be needed to select a weak desired channel that is near a strong undesired channel. For CATVs which provide many channels of signals at about equal signal strengths, the requirement may not be as difficult to satisfy. The YIG tunable filter [16] which is capable of covering the whole UHF range from a couple of hundred MHz to a few GHz could be part of the solution.

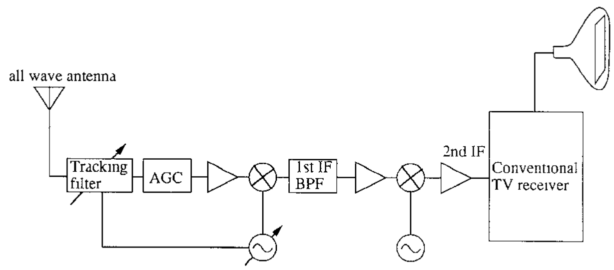

Fig 10. Block diagram of up-conversion tuner for all signal channels below UHF.

TABLE II
Technologies Needed for Up-Conversion Tuner

① Antenna for all wave reception
② Wideband tunable tracking filter from 50 MHz to 2 GHz
③ Wideband tunable local oscillator
④ Low distortion mixer
⑤ High selectivity 1st IF bandpass filter
⑥ Prescaler IC for 10 GHz or higher frequencies

C. Phased Array System

As satellite transmitted media expands, the noise figure of the front-end devices decreases, an active phased array antenna for reception of signals from multiple satellites will hopefully excite the consumer TV market. Fig. 11 shows the multiple satellite environment in Japan. A similar situation also exists in Europe and the United States. One may receive signals from the broadcasting satellite located in the south-west and from a few communication satellites with relatively low power located to the south. A phased array antenna [17] would certainly be convenient for reception of these multiple satellites.

A very interesting product is shown in Fig. 12, courtesy of Nippon Steel Company. The "Wave Chaser" as it was named can be installed on the top of moving vehicles and used to search for the broadcasting satellite. A flat-panel antenna is contained on a rotatable disc with a

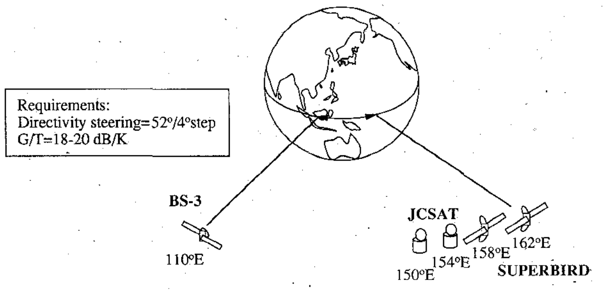

Fig. 11. Active Phased Array Antenna for Multiple Satellite Reception.

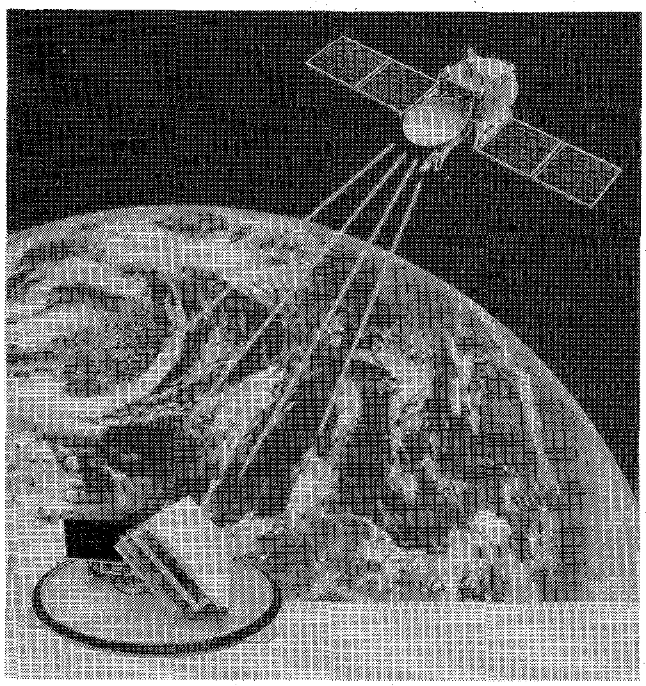
Fig. 12. "Wave Chaser" by Nippon Steel.

cover, and the direction is mechanically changed by electronically sensing the input microwave power. A phased array antenna, as suggested here, may improve performance.

D. Millimeter-Wave Devices and Systems

The development of high frequency solid state devices [18], [19] has now advanced to the point where one can expect exploitation of the Terahertz range. The HET (hot electron transistor) with an estimated transition time of 0.3 psec is an example [20]. In the Terahertz range, the electromagnetic waves exhibit characteristics similar to those of light, with the benefit of much easier signal handling. There are quite a few applications of millimeter waves, conceived and discussed so far, but the progress looks slow. We may have to focus our thinking on completely different aspects. As mentioned, millimeter waves act more like light waves and they may be a better solution than light for many applications. In any case, many entrepreneurs are expected to demonstrate their creativity for innovative products using these wavelengths.

E. Packaging

As we experienced in the Tuner ICs, the packaging of high frequency devices is of critical concern. It is expected that new materials will enable the design of cost effective packages with high performance. Some examples of new material systems are low temperature co-fired ceramics [21], liquid crystal polymers [22] and metal matrix ceramic composites [23].

IV. Global Scale Industrial Collaboration

The aforementioned future applications will require significant development efforts. Recently a number of collaborations between the world's top semiconductor manufacturers have been announced [24]. These reflect the changing structure of competition within the industry, for example, from company against company, to alliance against alliance. Clearly, there is a potential effectiveness of global industrial collaboration in the microwave and millimeter-wave arena. The technology of microwave and millimeter-wave monolithic integration has advanced significantly. Therefore, I think now is the time to set truly ambitious targets and work toward them. The more ambitious the target is, the more effective the industrial collaboration, and consequently the greater the impact of achievement. We should begin to develop cooperative plans for achieving this global technology transfer now.

Acknowledgment

The author would like to thank Dr. A. T. Murphy of DuPont, Dr. J. Kasahara and Mr. Y. Murakami of Sony for stimulating discussions. He is grateful for Mr. K. Miyata of Nippon Steel who kindly provided technical information for this paper. The author would also like to thank the IEEE Microwave and Millimeter-wave Monolithic Circuits Symposium Committee especially Dr. R. S. Kagiwada, Dr. A. Chu and Dr. Ho Huang for encouragement on this work.

References

[1] M. Ibuka, "How Sony developed electronics for the world market," *IEEE Trans. Eng. Manag.*, vol. EM-22, no. 1, pp. 15-19, 1975.
[2] J. Bardeen, private communication.
[3] L. Esaki, "New phenomenon in narrow germanium p-n junctions," *Phy. Rev.* 109, pp. 603-604, 1958.
[4] S. Watanabe, *Semiconductor Devices for Electronic Tuners*, ch. 5, New York: Gordon and Breach, 1991, pp. 130—138.
[5] T. Okanobu, T. Tsuchiya, K. Abe and Y. Ueki, "A complete single chip AM/FM radio integrated circuit," *IEEE Trans. Consumer Electron.*, vol. CE-28, no. 3, pp. 393-407, Aug. 1982.
[6] M. Ayabe, O. Matsuda, M. Dosen, S. Santa, and N. Watanabe, "An improved etched buried heterostructure laser with reduced threshold current," *Jpn. J. Appl. Phys.*, vol. 19, supplement 19-1, pp. 399-402, 1980.
[7] T. Mimura, S. Hiyamizu, T. Fujii, and K. Nanbu, "A new field-effect transistor with selectively doped GaAs/n-$Al_xGa_{1-x}As$ heterojunctions," *Jpn. J. Appl. Phys.*, vol. 19, no. 5, pp. L225-L227, 1980.
[8] Y. Mori, O. Matsuda, M. Ikeda, K. Kaneko, and N. Watanabe, "$Al_xGa_{1-x}As/Al_yGa_{1-y}As$ visible lasers grown by MOCVD," *J. De Physique, Colloque C5*, supplément au n°12, Tome43, pp. C5-271-279, 1982.
[9] T. Mamine, T. Oda, and O. Yoneyama, "New class of gain guiding

laser with a tapered-stripe structure," *J. Appl. Phys.* vol. 54 no. 8, pp. 4302-4304, 1983.
[10] H. Takakuwa, Y. Kato and S. Watanabe, "Low-noise HEMT fabricated by MOCVD," *Electron. Lett.*, vol. 21, no. 4, pp. 125-126, 1985.
[11] N. Watanabe, Y. Mori, and H. Kawai, "Superlattices and superstructures grown by MOCVD," in *Thin Film Growth Techniques for Low-Dimensional Structures*, New York: Plenum, 1987, pp. 115-136.
[12] H. Nakajima, "The conception and evolution of digital audio," in 1989 *IEEE Int. Solid-State Circuits Conf. Rec.* pp. 60-62.
[13] Y. Konishi, "GaAs devices and the MIC applications in satellite broadcasting," in *1990 IEEE Microwave and Millimeter-Wave Monolithic Circuits Symp. Dig.* pp. 1-6.
[14] A. Morita, *Made in Japan*, Collins, 1987.
[15] H. Kawasaki, M. Wada, Y. Hida, C. Takano, and J. Kasahara, "10K gate GaAs JFET sea of Gate," in *1990 IEEE GaAs IC Symp.*, pp. 135-138.
[16] Y. Murakami, T. Ohgihara, and T. Okamoto, "A 0.5-4.0 GHz tunable bandpass filter using YIG film grown by LPE," *IEEE Tran. Microwave Theory Tech.*, vol. MTT-35, no. 12, pp. 1192-1198, 1987.
[17] R. Carandang, J. Yonaki, W. L. Jones, R. E. Kasody, W. Lam, and L. C. T. Liu, "A K-band HEMT low noise receiver MMIC for phased array applications," in *1991 IEEE MTT-S Int. Microwave Symp. Dig.*, pp. 521-524.
[18] H. Wang, G. S. Dow, K. Tan, J. Berenz, T. N. Ton, T. S. Lin, P. Liu, D. Streit, P. D. Chow, and B. Allen, "A high performance W-band monolithic pseudomorphic InGaAs HEMT LNA," in *1991 IEEE/MTTS Int. Microwave Symp. Dig.*, pp. 943-946.
[19] K. W. Chang, H. Wanh, K. Tan, T. H. Chen, J. Berenz, G. S. Dow, D. Garske, A. C. Han, and L. C. T. Liu, "A W-Band Monolithic Pseudomorphic InGaAs HEMT Downcoverter," in *1991 IEEE Microwave and Millimeter-Wave Monolithic Circuits Symp Dig.*, pp. 55-58.
[20] K. Taira, F. Nakamura, K. Funato and H. Kawai, "Room-temperature operation of GaSb/InAs hot electron transistors grown by MOCVD," *1990 Inst. Phys. Conf.*, Ser. No. 112,; ch. 7, pp. 489-494.
[21] H. C. Bhedwar, A. L. Eustice, S. J. Horowitz, F. K. Patterson, and H. T. Sawhill, "Low temperature co-fired ceramic tape system-An overview," in *Proc. SAMPE Electronic Materials Conf.*, Society for the Advancement of Material and Process Engineering, June 1987, p. 720.
[22] DuPont Co. Product Sheet on Liquid Crystal Polymers.
[23] D. White, S. Keck, I. Smith and A. Silzars, "New high ground in hybrid packaging," in *Hybrid Circuit Technology*, Libertyville, IL: Lake Publishing/An IHS Group Company, 1990.
[24] Editorial, *The Japan Times*, July 8, 1992.

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