

Three-Dimensional MMIC and Its Evolution to WLCSP Technology

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The history of multilayered, three-dimensional monolithic microwave integrated circuit (3-D MMIC) technology is described here. Although significant researches were carried out in the second half of 1990's, still there were many twists and turns before and after the era. Since 2008, an aggressive and realistic development of 3-D MMIC Wafer Level Chip Size package (WLCSP); for extremely low cost and surface-mount compatible MMIC products, has been performed to provide a one-stop solution for radio-link equipment developers. This paper will be an example that indicates importance of continuous motivations.

Keywords: history, MMIC, multilayer, three-dimensional, WLCSP, high integration, low cost

1. Introduction

An exciting program on monolithic microwave integrated circuit (MMIC) technology was pursued on from nearly 1983 to 1991, including its design and fabrication equipments, mainly in USA and Europe. In the era, "MMIC" was a very new concept which meant integration of microwave and millimeter-wave circuits on a die. By incorporating the CAD and measurement tools developed in the program, Japanese researchers joined and contributed to the progress of the technology. The program was named "MIMIC Program" by Defense Advanced Research Project Agency (DARPA), USA. The title MIMIC means Monolithically Integrated Microwave Integrated Circuit. The author started his research on MMIC in 1983: same as the start of the program, hence, he is recognized as a starter in Japan. Four years later, he and his colleagues took part in challenges on highly integrated MMIC technology which was a target issue for both the program and his team. One of the main subjects was the Multi-layered MMIC. It had advanced, via its renewal to the three-dimensional MMIC (3-D MMIC), to the wafer level chip size package technology, WLCSP in short. The origin was first a really simple idea, but it became a big tree through a long-term technical evolution. This paper describes firstly a fruitless era with the passive multi-layer MMICs, secondly an aggressive era with the active device-rich 3-D MMIC transceivers, and thirdly current fruitful era with the WLCSP concept by incorporating which package-less and low cost microwave components are pushed in to commercialization. This paper describes the author's experience that an idea can be matured through changes in the way of thinking and engineering.

2. Request for MMIC Size Reduction

A prototype MMIC was published first by Plessey Company in the middle of 70's, where it was demonstrated that microwave analogue circuits can be integrated on a semiconductor die⁽¹⁾. This triggered a worldwide MMIC researches, and the gradually increasing publications on

MMIC made DARPA start the MIMIC Program. In the period and also currently, MMICs are designed in the fashion to form microwave circuitry directly on a die (see Fig. 1). Transistors, such as FET and HEMT, microwave transmission lines, capacitors and resistors, are integrated on a die. However, because MMIC is usually a GaAs-based expensive IC incorporating microwave transistors such as a GaAs field effect transistor (FET) and a GaAs high electron mobility transistor (HEMT), it has been strongly required to miniaturize the die size in the design stage, and particularly the transmission lines which occupy a large area of the die. Hence, it has been a significantly important issue to shrink the passive components as well as the circuit layout.

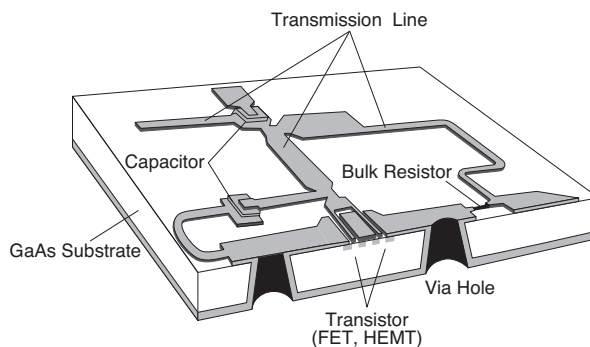


Fig. 1. An illustration of popular MMIC structure

3. Thin-Film Microstrip Line and Multilayer MMIC

It was our primary interest around 1988 to save the transmission line area by 90 percent. For the beginning of this section, an estimated area comparison between two microstrip lines (MSLs), as a function of substrate thickness H , is shown in Fig. 2⁽²⁾. For this estimation, the "area" is defined as the product of three line widths and a quarter-

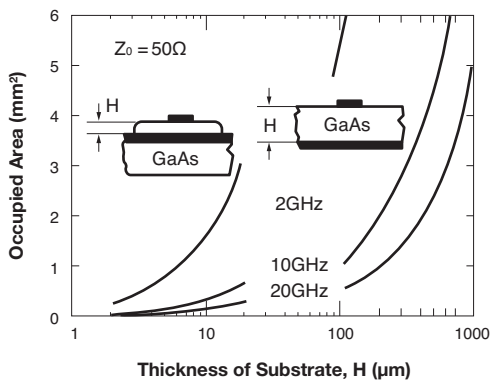


Fig. 2. Area comparison between two different micro-strip lines

wavelength. This figure indicates the dominant reason for the large area, as well as a method for drastic area shrink. The conventional MSL on GaAs substrate is expressed by the right cross-sectional structure. This MSL incorporates a strip conductor on the GaAs surface and the common ground metal on the backside of the GaAs. Hence, the line width and the electro-magnetic field become larger with the thickness H of the GaAs substrate, resulting in a larger occupied area. However, thinning the GaAs substrate is limited (nearly $100\mu\text{m}$ except for special MMICs) because of mechanical strength. By incorporating the left cross-sectional structure, instead of the right one, the area can be extremely reduced. In this structure, the GaAs is no more the substrate of MSL but only a mechanical support. This MSL incorporates the common ground metal beneath, and the strip conductor on the surface, of the thin dielectric film with thickness H . The strip conductor width reduces reciprocally to H . The thinner the film thickness is, the higher the transmission loss is. On the balance between loss and area, a film thickness of nearly $10\mu\text{m}$ was the best solution. Some loss should be considered in use of the thin-film MSL. This is an engineering to replace the area-shrink issue with the loss issue. For the first time SiON was used, however afterward, polyimide or BCB was selected for the thin film. The polyimide is currently used for lower loss, greater film thickness, and stable and less-stress fabrication. When the film thickness is $10\mu\text{m}$, the MSL strip width is nearly $20\mu\text{m}$. The spreading of the electro-magnetic field is 3 to 4 times the film thickness H , hence, coupling between line segments with a spacing nearly $4H$ can be ignored. This miniature transmission line is called Thin Film Microstrip (TFMS) Line⁽²⁾.

From this structure, so-called “Multi-layer MMIC” concept was derived easily. The authors and his colleagues started a research on highly integrated MMIC, advertizing that stacked TFMS-line passive circuitry shrinks MMIC die area effectively⁽³⁾⁻⁽⁵⁾. Meandering TFMS lines further shrink the line area because of possible narrow line spacing. TFMS lines located above and below a common ground are isolated. Miniature TFMS lines that are crossing on different layers have very small coupling to each other. Utilizing those features, a lot of miniature and functional/novel microwave passive circuits could be demonstrated. An example among them is illustrated in Fig. 3. This is a 4GHz

low pass filter composed of a pair of Japanese-character “田” shaped TFMS circuits (above and below a common ground metal) and L’s and C’s connecting the corners of the 田 circuits⁽⁶⁾. The 田 configuration is called Short-Line-Mesh (SLM). This circuit is an LC band-stop filter at low frequencies (nearly up to the LC resonant frequency) because the SLM is nearly equal to a point. Hence, its band stop characteristic is maintained at a frequency of $(LC)^{-1/2}$. It was demonstrated that the rejection bandwidth (out of band) can be very wide above the resonant frequency (7GHz) when asymmetric ports, Ports IN and OUT A, are selected, while undesired transmission bands above the resonant frequency are observed with symmetric ports, Ports IN and OUT B. The area occupied by the LPF is merely 1.4mm^2 . The asymmetric set of ports provides a complex phase cancellation system in the SLM, resulting in a LPF characteristic with a wide rejection band. This is a unique circuit, however, it is a problem that the LPF has a large in-band loss.

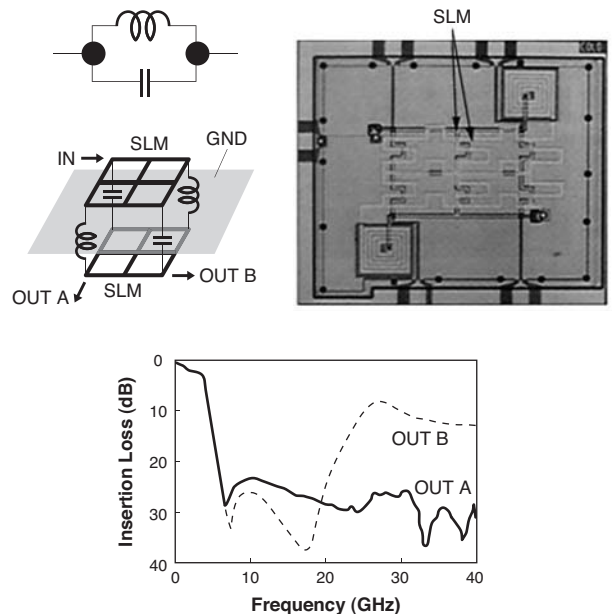


Fig. 3. A low-pass filter with stacked Short-Line Meshes

4. Receiver and 3-D MMIC

Any research that has a fatal short-coming generally loses its position. While the author was completing a transmitter MMIC set development and a high-power handset switch development using conventional MMIC technology (Fig. 1), he got an instructive indication. It was a comment that no research source would be given to any useless researches. After that, he started researches on receivers and transmitters integrated on a die, viz. single-chip transceivers. The above-mentioned developments using the conventional MMIC technology resulted in single function per

die. It was to be broken through toward multi-functions per die. The experience that he devoted himself to MMIC developments for on-going businesses was very instructive.

The multilayer structure can be much enhanced for high level integration when combined with active devices. In 1995, a 10GHz-band multi-layered MMIC receiver was designed, where a low-noise amplifier, three variable-gain amplifiers, a pair of mixers, two hybrid-function circuits (divider and combiner), and an LO amplifier were integrated in a 2mm x 2mm die. Total nine functions were integrated on such a small die. The two mixers and the hybrids were combined to construct an image rejection mixer*1. The IF signals are output from the IF ports with a phase difference of 90 degrees. The design was performed just in time the world was moving on to multi-functional MMIC research.

This advanced design derived a concept named "Three-Dimensional MMIC." It is because FETs and multi-layered passive circuits were stacked and connected vertically to each other to construct an effective functionality. The amplifier matching circuitry was stacked above and below the common ground on the middle metal layer. This was an effective method to achieve a 2mm x 2mm die. Through this and similar designs, the three-dimensional MMIC concept was extended to "Masterslice Three-Dimensional MMIC." The concept was additionally proposed in a paper. It has a close similarity to the well-known gate array technology. Including this concept, the technology name "Three-Dimensional MMIC" became familiar in international conferences. The microphotograph of a 10GHz-band single chip receiver, which is the first demonstration, is shown in Fig. 4⁽⁷⁾. The amplifier portion is magnified in Fig. 5, where the stacked impedance matching circuits make look intertwined.

The masterslice three-dimensional MMIC is a unique

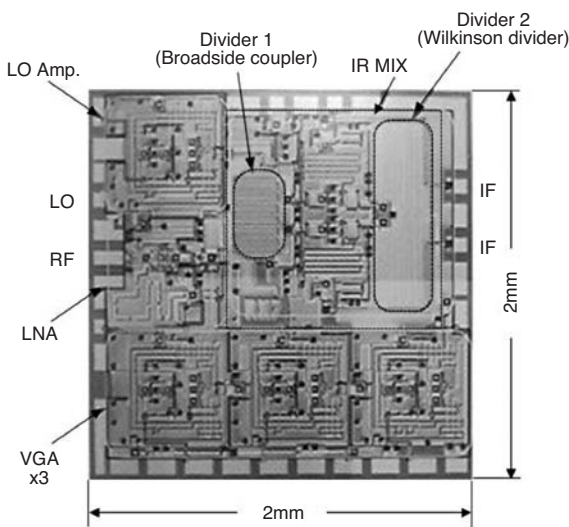


Fig. 4. An X-band receiver single-chip integrated by using three-dimensional MMIC technology

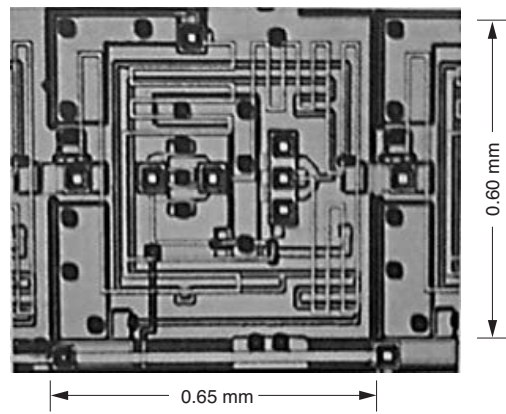


Fig. 5. The microphotograph of an amplifier in the receiver MMIC

design technology using a masterslice wafer with arrayed bulk components; FETs, MIM capacitors, and resistors⁽⁸⁾⁻⁽¹⁰⁾. The features of the three-dimensional MMIC such as; narrow line width and line-to-line spacing, coupling-free crossing on different layers, and flexible positioning of common ground, are maintained, resulting in a high level integration. The conceptual structure and usage of master array are illustrated in Fig. 6. By preparing general-purpose masterslice wafers, the turn-around time, TAT, can be extremely reduced. The wafer surface is selectively and widely covered with common ground metal according to designed circuits and subsystems. This provides a large area for passive microwave circuitry that is constructed with TFMS lines. The passive circuitry and the bulk components are

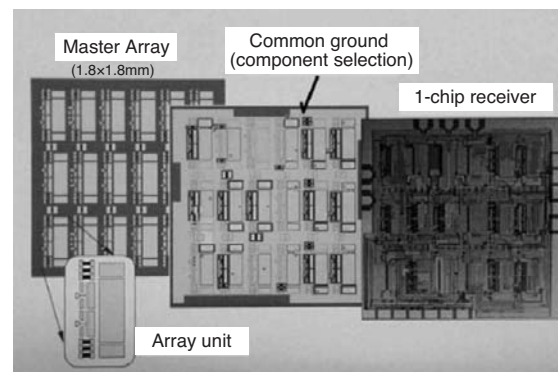
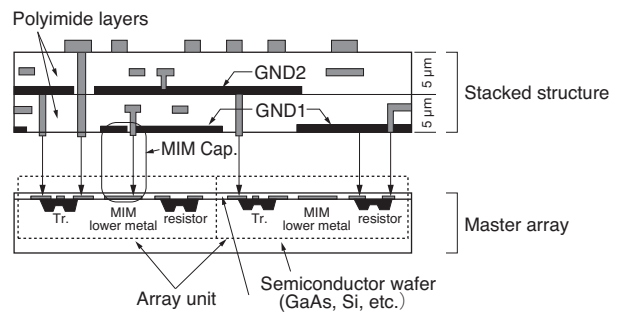


Fig. 6. The conceptual structure and usage of Maste-slice

connected vertically with tiny vias, completing whole circuit implementation. This design method can also be easily applied to not only insulating GaAs substrate but also conductive silicon substrate, because the common ground electro-magnetically isolates the substrate and the circuitry. This concept was proposed in 1995, and its research and demonstrations continued until 1998.

5. Situation Change and Technology

The three-dimensional MMIC research was resumed after several years had passed. A reason for the interruption is that the technology was not welcomed by the production line persons as well as product design persons, for each of their products was a single function device. No functional integration was in their business range. Additionally, they thought that any market competitive MMICs could not be performed with the TFMS line loss. It was nearly the same in US. They had been facing many works to do such as industrial, scientific and medical (ISM) band and military MMICs. No fruitful advertising effect on 3-D and master-slice MMIC was obtained from 1998 to 2003. During the period, the author engaged in development of a 38GHz linear voltage-controlled oscillator (VCO) as the core of FMCW automotive radar systems (Frequency modulated continuous wave is called FMCW in short)⁽¹¹⁾, and then engaged in improvement of a 10Gbps optical receiver module for oscillation-free operation and mass production⁽¹²⁾. He also developed a prototype 40Gbps optical receiver module⁽¹³⁾. Starting the production of automotive radar modules, various trouble shooting jobs and cooperation with product line engineers were needed to achieve mass-productivity. Hence, in the period, the 3-D MMIC was not pursued on.

As gradually increasing the sale of automotive radar modules, the radar system had been modified for lower cost. Low-cost radar sets for public cars became an urgent target for market expansion. The Daimler-Benz was consociating European companies and universities to develop low-cost public car radars. The cost target was set at a very low level; no comparison to conventionals, where the GaAs MMIC technology was thought to be poor for the target. The consortium selected SiGe HBT (Ge-doped silicon hetero-junction bipolar transistor), however, it was not available in our foundry. This situation triggered the use of the 3-D MMIC technology for single chip integration and low cost. Our design department decided to choose it. From 2006 to 2007, a 76GHz automobile radar module using 3-D MMICs was designed and demonstrated. This module consists of a 76GHz transceiver 3-D MMIC, a 76GHz four-inputs/single-output switch 3-D MMIC, and a 9.5GHz FMCW VCO MMIC.

A 76GHz module as a demonstration vehicle and a transceiver MMIC in it are shown in Fig. 7⁽¹⁴⁾. While the module performance was nearly acceptable, the cost was estimated to be higher than the requested. A very compact integration had been achieved. However, it needed many bond-wirings because of face-up assembly of MMIC dies. Rectangular holes in PCB, into which MMIC dies were attached, should be made for shortest wirings between

MMIC and PCB. It was indispensable at 76GHz. An additional impedance matching circuitry on PCB was also necessary for each 76GHz interface. That is to say the fabricated module was only a demonstration vehicle. One important result was that the potential for high-level integration and reasonable chip cost saving was recognized, and then the technology shifted to three-dimensional WLCSP technology to be explained in the next section. A 76GHz MMIC chipset is currently being finalized with the WLCSP technology⁽¹⁵⁾.

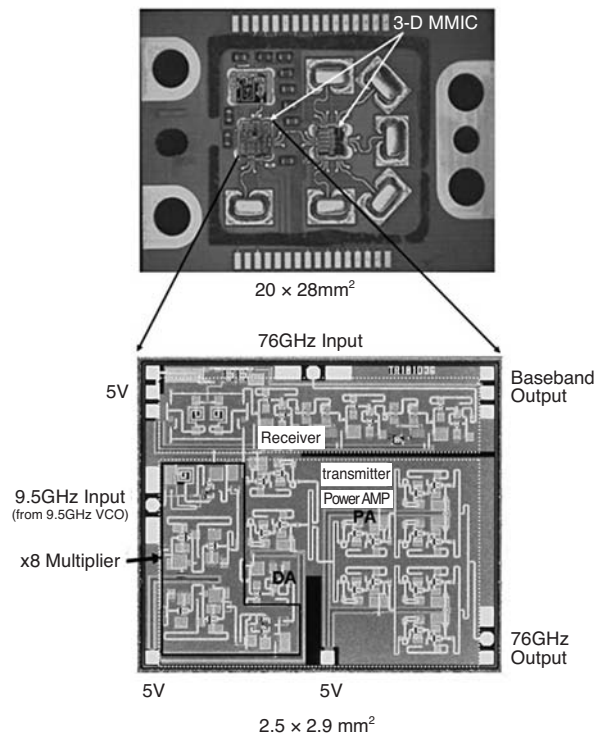


Fig. 7. A 76GHz automotive-radar transceiver module with use of the three-dimensional MMIC technology

6. WLCSP Technology for Low Cost

The electronic devices divisions of Sumitomo Electric Industries, Ltd. have been developing mainly power amplifiers (PAs) for point-to-point communications between base stations. GaN HEMT is currently the star device in the business. On the other hand, frequency converters (mixer functions such as down-converter and up-converter) were out of sight. A very limited number of mixers had been commercialized, resulting in difficulty to receive frequent orders. It is because, generally, many set makers often design mixers on PCB by themselves, or incorporate mixer products of US companies who monopolize the mixer market. Mixers for microwave communications need to provide a good LO-to-RF leakage suppression or image-rejection operation as well as frequency conversion^{*1}. The conventional in-house

mixer MMIC design was behind the US companies due to a larger die size. The lower design potential made it further difficult to integrate required LO amplifier and frequency multiplier in a die. Hence, mixer designers had not been cultivated.

Meanwhile, our expanding PA business is now facing a new situation. The business has been pursued on selling Power HEMTs, PA MMICs, and DA MMICs. This business style strongly depends on the level diagrams in customers' transmitters, currently having risks for being replaced by competitors' PA products. Furthermore, the competitors are starting a new business strategy that provides whole transceiver components designated for each radio-link band. This provides so-called One-Stop Solution. To compete with this change, our company needed to start the new strategy with a new technology, which is a new generation of three-dimensional MMIC technology. A department director who roles the core leader of the business proposed and pushed forward a flip-chip three-dimensional MMIC concept called "Wafer Level Chip Size package," WLSCP in short. The WLSCP concept is illustrated in Fig. 8. A humidity proof three-dimensional MMICs with common ground metal on the top surface is fabricated, and solder balls are periodically allayed on to the I/O pads and ground on a wafer. Only by cutting out to dies, each die can be a SMT product that is compatible with conventional ones in SMT packages^{*2}. The die is, in assembly process, flux transferred, mounted on PCB, and fixed on PCB after a popular solder reflow process. Various circuit functions are integrated in a small die with the 3-D MMIC

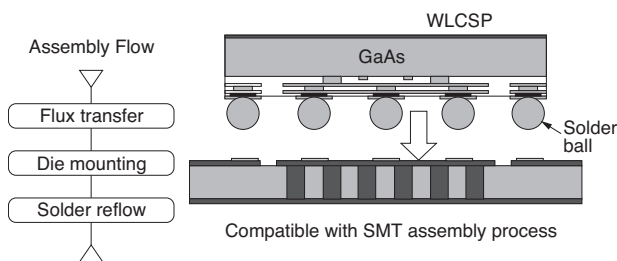
technology.

This technology eliminates the need for both wiring and packaging, contributing to save the production cost by more than 50%. A competitive scenario, in which a high functional integration for flip-chip assembly is available, was prepared. The common ground metal covers the whole microwave circuitry. The strip conductors for transmission line are formed on the GaAs wafer surface or on a polyimide layer near the wafer surface. The transmission lines are called inverse TFMS lines and work similarly to TFMS lines, and then, effective for both miniaturization and high integration of functional circuits. Furthermore, WLSCP dies can be batch assembled on PCB through a solder-reflow process, and the tiny solder balls arrayed on a die provide a good interconnection even at millimeter-wave frequencies. Though the flip-chip concept is not new, the flip-chip structure combined with the three-dimensional MMIC technology has been newly established via several-year process development. This is an important progress.

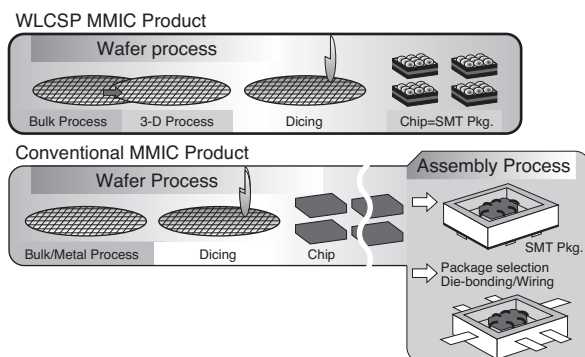
7. Developed WLSCP Mixers^{(16),(17)}

A 13-15GHz (for VSAT^{*3}) up-converter developed in the fashion of the WLSCP is shown in Fig. 9. The die size is 2.4 x 2.4 mm². A pair of single balanced mixers^{*1} are combined with couplers and a LO amplifier to construct a double balanced mixer.

The LO amplifier is integrated to provide an enough level of LO signal to each mixing device (PHEMT). Its circuitry is located along a side of the die to save area. This unique and flexible layout is effectively performed in the three-dimensional MMICs. The saturated output power of the LO amplifier is 16dBm in a frequency range as wide as between 10GHz and 23GHz (hence, this can be used additionally for 18-23GHz band), where a core circuit named Dual-HEMT^{*4} is incorporated to perform high gain and broadband operation⁽¹⁸⁾. This topology offers higher gain and design easiness than cascode-FET^{*4} often used in



(a) Structure and assembling flow



(b) Production flow

Fig. 8. Three-dimensional WLSCP technology
(a) Structure and assembling flow
(b) Production flow

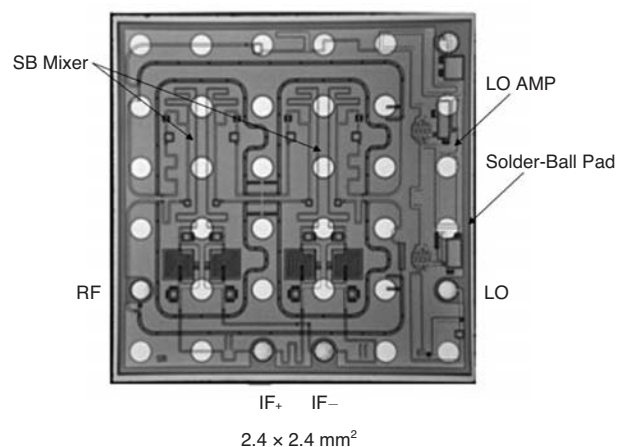


Fig. 9. Microphotograph of a double balanced mixer with the WLSCP structure

1990s. The unit mixer in the balanced mixers is a resistive mixer^{*5 (18)}. The PHEMT in the unit mixer is excited by a large LO signal at the gate and provides an ON/OFF switching (non-linear conductance) between the drain and the source. This mixer is superior in linear operation, while it exhibits a conversion loss, and its dc-bias free operation is convenient in high-level integration of mixers. The circuit schemes and performances of a LO amplifier and a unit mixer are shown in **Fig. 10**. Each balanced mixer is a combination of a pair of unit mixers and a pair of 90-degree couplers.

By combining these functional components, a double balanced mixer was realized as shown in **Fig. 11**, where a circle with cross means a unit mixer, a rectangular with cross

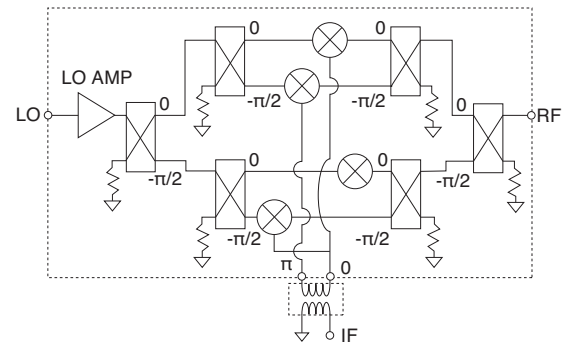
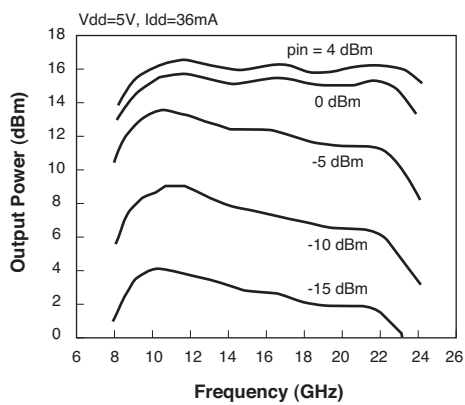
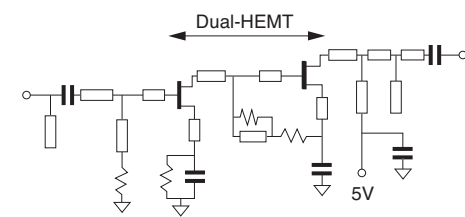
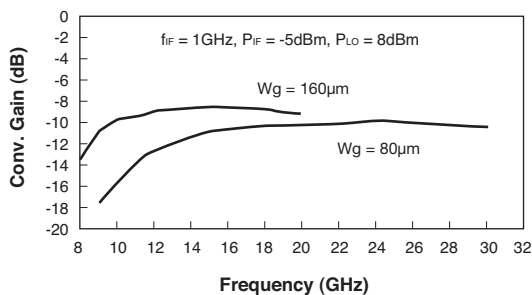
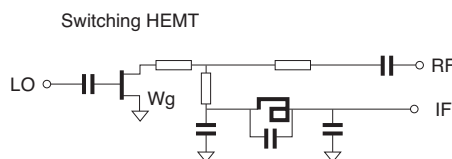


Fig. 11. The topology for double-balanced mixer



(a) LO amplifier



(b) Unit resistive mixer

Fig. 10. Performances of LO amplifier and mixer
(a) LO amplifier
(b) Unit resistive mixer

means a 90-degree directional coupler, and 0 and $-\pi/2$ mean signal phases at the coupler ports. The single balanced mixer is constructed with the unit mixers and the couplers so that the LO signal leakages are canceled, as well as the RF signals are combined in phase, at the RF port⁽¹⁸⁾. The coupler is a broadside coupler with stacked TFMS strip conductors. In this WLCSP, the ground metal along the stacked strip conductors is removed for better coupler performance. The LO leakage to the IF ports is suppressed with a LPF. The double balanced mixer is formed in the same manner, where the IF signal is divided out of phase with use of an external balun (transformer).

The mixer linearity is important to be used for communication equipment. This requirement is satisfied by using the resistive mixer with a high level of LO signal input. The linear characteristic is typically indicated with the third-order input intercept point (IIP3)^{*6}. The IIP3 of the up-converter was as high as 20dBm. A die assembled on PCB and the measured performances are shown in **Figs. 12 and 13**. **Figure 12** gives a photo of an up-converter (black square) directly attached to PCB. The up-converter die and a commercially available balun (white rectangular) are fixed in the same reflow process. The up-converter was measured in three conditions as indicated in **Fig. 13**; face-up measurement with RF probes, flip-chip measurement on PCB (flip-chip assembly 1), and flip-chip measurement

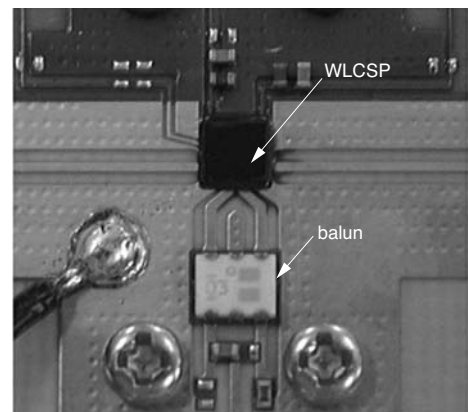
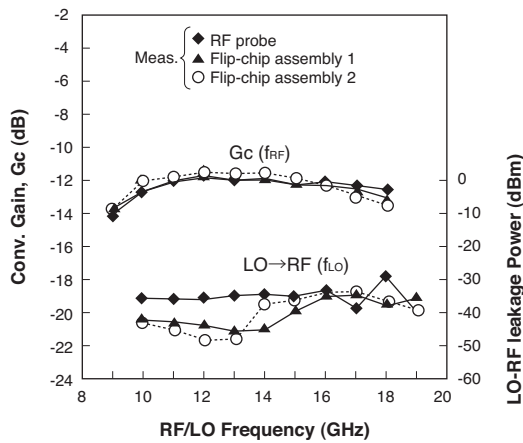
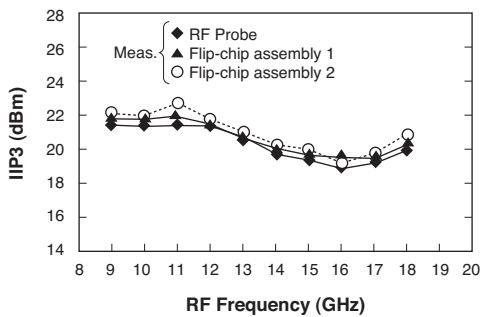


Fig. 12. A WLCSP die flip-chip assembled on a PCB



(a) Conversion gain and LO leakage power



(b) Third-order input intercept point (IIP3)

Fig. 13. Evaluation results for a WLCSP up-converter
(a) Conversion gain and LO leakage power
(b) Third-order input intercept point (IIP3)

with LTCC interposer on PCB (flip-chip assembly 2). A good correlation among the measurements was confirmed. This proves that the flip-chip assembly of WLCSP die can be done with no troubles or performance degradation. The LTCC interposer is not necessarily used, but important for some customers. The product number for this up-converter is SMM5138.

In the same manner, down-converters and low-noise amplifiers were developed for the 13-15GHz application with product numbers as SMM5722 and SMM5139. Furthermore, to prepare for all the radio-link bands, 18-23GHz band and 24-30GHz band WLCSP components have been under development. An at-a-glance of the mixer WLCSPs are summarized in Fig. 14. Low-noise amplifiers are not shown because the circuits are same as that of down-converter LNAs. The WLCSP mixers for above 18GHz include a frequency multiplier (enclosed with dotted lines) in the LO path. It is to make use of a LO input frequency below 15GHz, making oscillator lineup preparation much easier.

As illustrated in Fig. 15, the WLCSP dies requested for a radio-link MMIC set are power amplifier (PA), driver amplifier (DA), low-noise amplifier (LNA), and up- and down-converters (U/C, D/C), where the LNA and D/C are integrated in a WLCSP die in our development. When using the current InGaP PHEMT process, all the components except PA are possibly developed. PAs with an output

	13-15 GHz	18-23 GHz	24-30 GHz
Up-converter	RF IF ₊ IF ₋	RF (f _o) IF _s	RF (f _o) IF _s
Down-converter	LO IF _o IF _i	RF (f _{o/2}) IF _s	LO (f _{o/2}) IF _s

Fig. 14. At-a-glance of WLCSP mixers

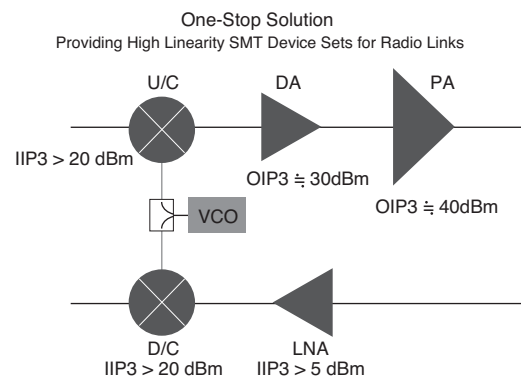


Fig. 15. Typical radio-link transceiver components

power level of up to 2W is expected to be developed by establishing a GaN HEMT WLCSP technology (DA will possibly be a GaN HEMT WLCSP in this situation). This WLCSP program supports our scenario for the One-Stop-Solution. The MMIC technology has been expected as one of the main technologies for radio-link business. Now, the WLCSP technology is expected to develop further due to its high competitiveness and originality.

8. Conclusion

A research on multilayer MMIC had started in 1987, and 10 years later, the multilayer structure was extensively applied to integration of active circuits. It was named Three-Dimensional MMIC. Further progress was made after another 10 years, where the three-dimensional MMIC concept for face-up assembly was improved to WLCSP for flip-chip assembly and low cost. This paper simply described the history. For the author, who has pursued on the technology development, the 20-year history is extremely impressive. Continuing do-the-best and do-break-through could be performed with invincible wisdom and by keeping the original idea in mind. The author would like to thank in advance the colleagues for their efforts to gain customers' satisfac-

tions with mass produced WLCSP MMICs.

The author would like to thank Mr. Yuichi Hasegawa of Sumitomo Electric Device Innovations, Inc. (SEDI) for his pioneering planning of WLCSP, and Mr. Tomio Satoh of SEDI, Mr. Miki Kubota, and their group members for their design efforts.

Technical Term

*1 Suppression of LO leakage and image⁽¹⁸⁾ : Frequency conversion function is usually used in receivers and transmitters. A transistor for frequency mixing is excited into a non-linear state by a LO signal. There are two types of requirements on signal suppression.

A part of the LO signal which leaks to the RF port degrades the transmitter performances, hence, suppression of the LO leakage is necessary. The mixer that performs efficient LO-leak suppression without filters is called "Balanced Mixer."

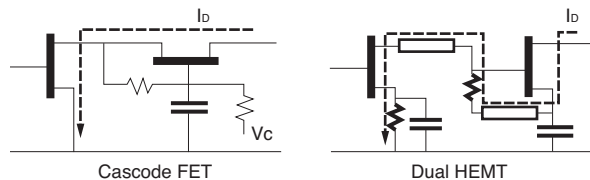
One of the input signals besides the LO signal frequency is the desired signal and the other is "Image Signal" that is undesired for communication. The mixer that performs efficient image suppression is called "Image-rejection Mixer."

The mechanisms are based on phase cancellation in which undesired signals are combined out of the phase at the mixer output port.

*2 SMT package : SMT stands for surface mount. The metal contacts are formed on the backside of package so as to be fixed on PCB through solder reflow. Low-cost ceramic and plastic packages are made in this fashion.

*3 VSAT : VSAT stands for Very Small Aperture Terminal. The VSAT system provides a data transmission between data-gathering centers and trucks or convenience stores.

*4 Dual-HEMT and Cascode-FET⁽¹⁸⁾ : Both transistor structures are in the current reuse topology. A continuous dc-current path is formed through two transistors such as HEMTs and FETs (see the figures shown below). The Cascode-FET is a combination of common-source FET (CSF) and common-gate FET (CGF). The Dual-HEMT is a combination of a pair of CSFs and a series dc-current path is formed by means of capacitive shunt at the second HEMT's source. These are often used for effective gain enhancement.



*5 Resistive mixer⁽¹⁸⁾ : Resistive mixers operate by switching the drain-source conductance of FET or HEMT. When a LO signal is applied to the gate of FET/HEMT with no dc bias, the channel resistance changes between nearly infinite and low values. This prepares a nonlinear conductance G_{DS} as function of LO voltage.

Applying an RF or IF signal to the nonlinear characteristic, an IF signal or RF signals besides the LO frequency are generated, performing a frequency conversion. For an input signal (IF or RF) level at below the knee voltage, the nonlinearity is stable. Therefore, a high linearity in the mixer operation is expected.

*6 IIP3 and OIP3 : IIP3 stands for Input Intercept Point, and similarly, OIP3 for Output Intercept Point. When a couple of input signals (f_1, f_2) with the same amplitude incident to a device, the third inter-modulation components, IM3, appear at the output port. The Output-input power characteristics for signals (f_1, f_2) and the IM3 components ($2f_2 - f_1, 2f_1 - f_2$) cross to each other at a point on each extrapolated straight line. The input power level for the cross point is IIP3 and the output one OIP3. These are often used to characterize the device linearity.

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