Business Prospects for Commercial mm-Wave MMICs

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MMIC manufacturers are now starting to introduce commercial devices operating at millimeter-wave frequencies, but several challenges must be addressed before these high-frequency MMICs can become a mainstream commercial success.

The following is excerpted from a recent report entitled *Commercial Applications for Millimetre-Wave MMICs*, by Jeff Powell and Dave Bannister, published by Technology Tracking, a partnership between QinetiQ, Europe's largest science and technology organization, and Institute of Physics Publishing. More information about the complete report is available at http://www.technology-tracking.com. The complete report includes a detailed analysis of the business and technological drivers at work in a range of current and emerging applications for mm-wave MMICs; a summary of efforts to deliver packaged and tested parts that meet the performance, cost and size criteria demanded by commercial end-users; the most-common device architectures and strategies for successful MMIC design; and profiles of organizations actively developing and marketing systems based on mm-wave MMICs.

Rapid progress over the past 50 years has yielded monolithic microwave integrated circuits (MMICs) that are small and cheap enough to form the fundamental building blocks for the revolution in mobile communications. These low-frequency MMICs, which typically operate around 1–2 GHz, are now widely exploited in wireless basestations and handsets, with industry figures now estimating the worldwide MMIC market to be worth US$2 billion per year. However, the mass-market appeal of wireless communications has commoditized the supply of these low-frequency MMICs. Manufacturers are under constant pressure to cut unit prices, while industry demand for microwave components is showing signs of declining, or at least levelling off. As a consequence, many MMIC suppliers are actively seeking new application areas that will command higher profit margins and drive future business growth.

A recent report, titled *Commercial Applications of Millimetre-Wave MMICs*, reveals that extending MMIC technology to millimeter-wave (mm-wave) frequencies has emerged as a crucial strategy for chip manufacturers, since a number of applications exist but only a few commercial products are currently available on the market. Such mm-wave MMICs would operate in the 20–100 GHz frequency range, which corresponds to wavelengths of a few millimeters. Devices operating at these frequencies have already been exploited in space and defense applications and are beginning to find applications in the commercial arena. The market for commercial mm-wave MMICs is expected to grow from US$163 million in 2003 to $400 million in

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2007, according to U.S. MMIC solutions supplier TriQuint.

Advantages of mm-Wave Operation

MMICs operating at mm-wave frequencies offer several major benefits over their low-frequency counterparts. For a start, the higher operating frequencies enable more information to be encoded in the signal, which make mm-wave solutions ideal for high-bandwidth, high-capacity communications systems. High-frequency MMICs also work well for applications requiring narrow antenna beams or high spatial resolution in a compact size, since the shorter wavelengths of mm-waves enable the use of smaller receiver and transmitter elements.

Another advantage is that the mm-wave spectrum encompasses frequency bands that are suited to both short- and long-range transmission, since relatively small changes in frequency can lead to large variations in the attenuation caused by atmospheric absorption (see Figure 1). This makes the 60-GHz band ideal for short-range communications, since the high attenuation at the frequency minimizes interference from nearby transmitters. In contrast, frequencies around 90 GHz are better for transmitting high-data-rate signals over extremely long distances.

These advantages have already been put to good use in space and military applications, but continuing advances in circuit design are enabling smaller and cheaper components to be developed for commercial end-users. For example, vendors of fixed-wireless equipment, such as Terabeam Wireless, Ceragon Networks, and Bridgewave, are exploiting mm-wave MMICs in 60-GHz communications links that support data rates in excess of 1 Gb/s—enough for enterprise customers to connect their internal Ethernet networks to the fiber infrastructure. Systems operating beyond 70 GHz are now being developed to provide data rates of up to 10 Gb/s over a range of up to 1 mi.

Satellite network operators are also eager to harness the benefits of higher frequencies. Two-way communications based on very-small aperture terminal (VSAT) satellite technology at 12–18 GHz already represents a significant commercial market for microwave MMICs, while next-generation systems at 26–40 GHz are set to be deployed in 2005/2006. These deployments, which will offer better services at lower cost by enabling smaller antennas, dynamic bandwidth allocation and narrower beams, are likely to fuel strong demand for mm-wave MMICs between 2004 and 2008.

For true mass-market success, however, mm-wave suppliers are looking to the emerging market for automotive anti-collision radar at 76–77 GHz. Radar-based systems providing adaptive cruise control are now being fitted to luxury cars, such as the Mercedes-Benz S-Class and the Volkswagen Phaeton, and falling component costs look set to open up the mid-price car market. Dan Green, TriQuint's director of broadband technology, estimates that 4.5 million mm-wave MMICs will be deployed for automotive radar applications by 2007, while total mm-wave MMIC usage in this market could approach 100 million per year by 2010.

Technologies for the mm-Wave MMICs

There is no doubt that mm-wave MMICs offer serious potential in the commercial marketplace, but the challenge for suppliers is to deliver packaged and tested parts that meet the performance, cost, and size criteria demanded by commercial end-users.

These demands are already being addressed at the chip level by the major developers and manufacturers of mm-wave MMICs, including TriQuint and Northrup Grumman in the United States and United Monolithic Semiconductor in France. As a result, it is now generally agreed that the latest generation of MMIC manufacturing processes can deliver the gain and bandwidth performance required for applications at frequencies of up to 100 GHz.

Most of these commercial high-frequency MMIC processes are based on GaAs pseudomorphic heterojunction electron mobility transistors (pHEMTs). In a high-electron mobility transistor (HEMT) device structure, precise epitaxial growth techniques are exploited to form a two-dimensional electron gas in the active region. Electrons confined in this region have superior transport properties, including high mobility and velocity, which allows HEMT device structures to achieve high operating frequencies and low noise figures.

These transport properties are improved still further in a pHEMT, a special class of HEMT in which the two layers

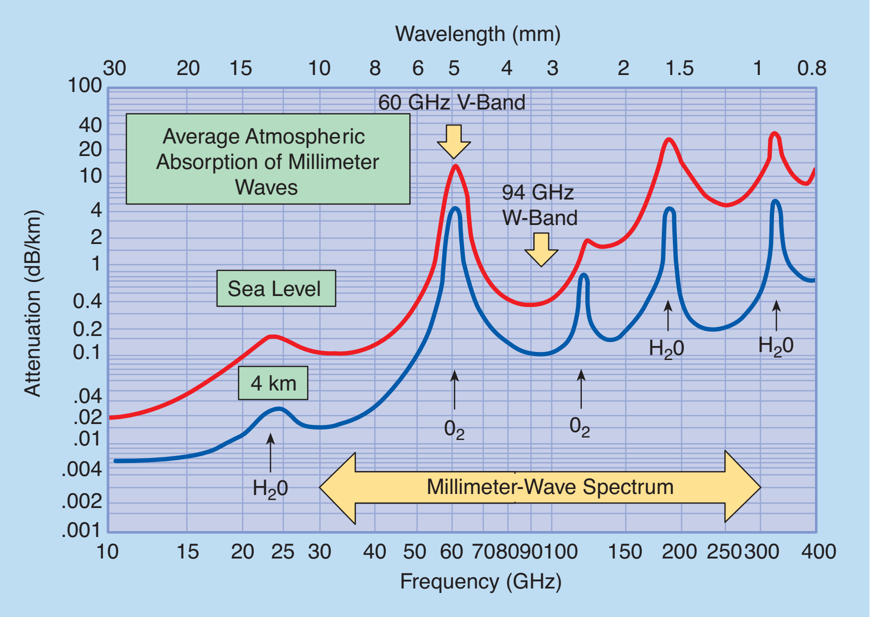

Figure 1. *Variations in the atmospheric attenuation of mm-waves provide windows for both short- and long-range transmission.*

that form the heterojunction are not lattice matched. The channel in most GaAs pHEMTs is a thin layer of undoped InGaAs with an indium content of 15–25%, which is separated by a thin spacer layer from an adjacent n-doped AlGaAs layer. The addition of indium to the channel results in improved electron mobility, while the extra heterojunction barrier helps to confine the carriers to the channel under all operating conditions.

GaAs pHEMTs offer good power and low-noise performance at frequencies of up to around 100 GHz. Indeed, a comparison of about 80 power MMICs reported by different organizations reveals that GaAs pHEMT devices are finding near universal application across the microwave and mm-wave spectrum (Figure 2). The solid line in the graph in Figure 2 shows the fall in output power with frequency that is predicted by device physics.

At the highest frequencies, slightly better performance is achieved by InP pHEMT MMICs. These devices are grown on InP substrates, which allows the indium content in the channel to be increased to 53% and beyond to achieve a significant improvement in electron mobility. This advantage is particularly beneficial for low-noise amplifiers, with InP pHEMTs being the only devices to deliver adequate gain performance at frequencies beyond about 120 GHz.

Future Trends for mm-Wave Technologies

While existing MMIC processes can produce high-performance devices operating across the mm-wave spectrum, intense R&D activity is continuing to increase the power output and achieve better low-noise characteristics over a wider frequency range. Much of the innovation stems from conventional compound semiconductors, with new device architectures based on GaAs and InP now emerging to provide better power performance at mm-wave frequencies.

Much recent attention has focused GaAs-based metamorphic HEMTs (mHEMTs), which are rapidly emerging as an easy-to-manufacture technology that matches the high-frequency performance normally associated with InP-based devices (see Figure 3). Such mHEMT devices exploit a special buffer layer that shifts the lattice constant by up to 5%, allowing InP HEMT structures with high indium content to be grown on GaAs substrates.

MHEMT wafers with high quality and good surface morphology have been demonstrated using buffer layers made from both InAlGaAs and AlGaAsSb. The main concern has surrounded the thermal conductivity of metamorphic buffers, since the lower thermal conductivity of the GaAs substrate with a metamorphic buffer leads to a higher thermal impedance. However, a solution to this problem could be found in the use of binary InP buffer layers.

Foundry services are now available for 0.15-μm mHEMT low-noise processes on 4-in wafers and 0.15-μm power processes on 6-in wafers, while the first mHEMT MMIC products are also appearing on the market. The first application of the technology is likely to be in low-noise amplifiers, where devices with 60–70 nm gate lengths and a channel indium content of between 75 and 80% have been used to create MMIC LNAs offering a noise figure of 2.3 dB with an associated gain of 13 dB at 94 GHz (Figure 3). MHEMT technology is also being investigated for high-efficiency power amplifiers operating above 20 GHz.

Interest is also growing in the use of InP heterjunction bippolar transistors (HBTs) for high-performance applications, since these devices deliver unparalleled current densities at frequencies of a few hundred gigahertz. Researchers at the University of Illinois in the US have reported the fastest InP HBT to date, with a cut-off frequency of 509 GHz and F_{max} of 219 GHz [1]. (The cut-off frequency, F_{t}, gives an indication of the intrinsic device speed and is useful for comparing basic device mechanisms. The maximum frequency of oscillation F_{max} includes the effects of parasitics and gives the best indication of the gain that can be expected from a correctly matched device in an MMIC. Amplifier

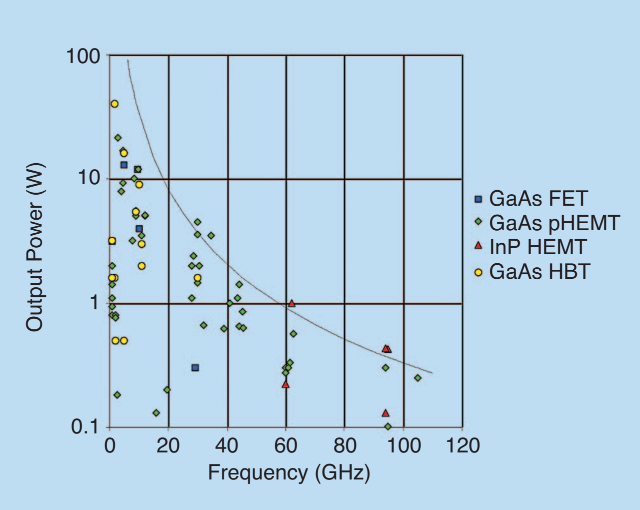

Figure 2. *The output power from MMIC power amplifiers reduces with frequency as predicted by device physics. Power amplifiers based on GaAs pHEMTs are used over a wide range of frequencies.*

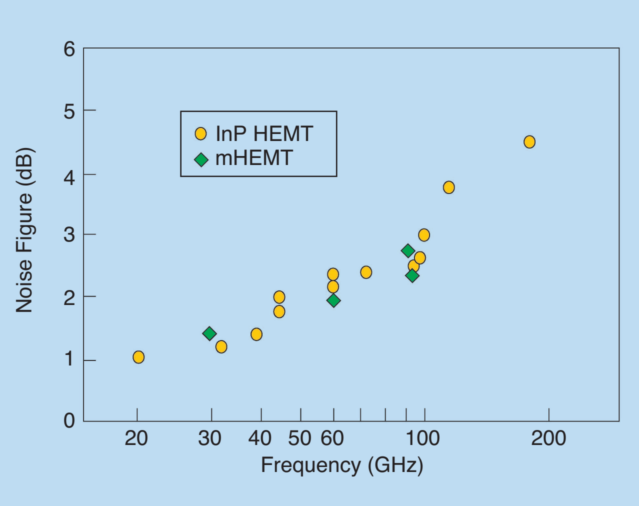

Figure 3. *The noise figure for the best reported MMIC LNAs shows that mHEMT-based MMICs offer the same high-frequency performance as those based on InP HEMTs. (Source: Commercial Applications for Millimetre-Wave MMICs)*

operation can be achieved at frequencies of less than 0.5 $F_{\max}$, while oscillator operation close to $F_{\max}$ is possible given a low-loss feedback network.)

InP HBT foundry services are now available from Vitesse Semiconductor in the United States, thanks largely to project funding from the Defense Advanced Research Projects Agency (DARPA). However, InP remains an expensive material system that requires specialist fabrication techniques, and challenges remain in scaling the device dimensions, further reducing the power consumption and enabling greater integration. As a result, InP HBTs are likely to be reserved for applications that require superior power performance, such as military radar and communications systems.

Emerging Materials

Other materials systems are also starting to challenge the dominance of traditional compound semiconductors for mm-wave applications. For example, silicon germanium (SiGe) technology—which exploits the same manufacturing processes as silicon-based CMOS—is rapidly emerging as a low-cost alternative to InP devices for low-power applications requiring operating frequencies of up to 100 GHz. SiGe technology also allows analog, digital, and RF functionality to be integrated into a single chip.

An SiGe HBT is similar to a conventional silicon bipolar transistor, except that the base is made from SiGe instead of silicon. The germanium content is typically graded across the base, which creates an accelerating electric field that increases the speed of electrons crossing the base, leading to higher operating frequencies.

SiGe HBTs can achieve cut-off frequencies of up to 375 GHz, rivalling the high-frequency performance of InP-based devices, but they cannot be used for high-power applications because their breakdown voltage is limited to about 3.6 V (Table 1).

Table 1. Comparison of device performance characteristics for SiGe HBTs and InP HBTs produced in a program supported by DARPA.

Performance metric	SiGe HBT	InP HBT
Breakdown voltage: BV_{ceo}, BV_{bco}	<2 V, 5V	>4 V, >8 V
Gain at 20 GHz	22 dB for 0.12 × 11 μm² device	>20 dB for 0.4 × 11 μm² mesa device >35 dB for 0.4 × 6 μm² self-aligned device
Substrate cross talk	Moderate	Low
Linearity	Good	Excellent
1/*f* corner noise frequency	400 Hz	×1 kHz
20-GHz noise figure	1.4 dB	0.7 dB
Best reported F_t, $F_{\max}$ (GHz)	350, 170	370, 280 (0.35 × 5 μm² device)
	270, 260 (0.12×2.5 μm² device)	300, 300 (0.4 × 11 μm² device)
Current density at max F_t	Excellent	Excellent

Table 2. The semiconducting properties of SiC and GaN make them ideal for high-power devices.

	Si	GaAs	4 HsiC	GaN
Bandgap eV	1.12	1.43	3.26	3.36
Thermal conductivity W/cm K	1.5	0.5	3.3–4.8	1.5
Breakdown field MV/cm	0.3	0.3	2.5	2.5
Saturated electron velocity × 10^7 cm/s	1.0	1.0	2.0	1.2–2.7
Electron mobility (cm²/V s) at 2×10^{17} cm³	600	4,000	400	1,000–2,000
Wafer size (mm)	300	150	75	50
Price ($/in²)	~1	<10	700	>1,000s

The latest SiGe foundry service offered by IBM exploits 0.18-μm feature sizes to achieve operating frequencies from 40 to 100 GHz, while work is continuing on developing manufacturing processes for SiGe HBTs operating at up to 200 GHz [2]. Potential applications include high-speed communications systems at 60 GHz and beyond, and automotive radar systems at 77 GHz, which both require low-cost RF components.

One problem with SiGe technology is that silicon wafers cannot exploit traditional MMIC processes since conventional transmission-line structures require a semi-insulating substrate. However, alternative processes have been developed to enable SiGe technology to support high-quality passive elements, including high-quality inductors and capacitors, which has allowed the development of MMIC solutions. For example, researchers at Robert Bosch and the Ferdinand-Braun Institute in Germany have used SiGe MMICs to demonstrate sensor front-ends for automotive applications that operate at frequencies beyond 100 GHz [3]. This work exploited a pre-production 0.13-μm process from IBM, which produces SiGe HBTs with cut-off frequencies of about 200 GHz.

For high-power performance, however, device designers are turning to wide-bandgap materials, such as silicon carbide (SiC) and gallium nitride (GaN), which have the potential to increase the power performance of MMIC power amplifiers by a factor of ten. These materials offer much higher breakdown fields and saturated electron velocities than GaAs, as well as far superior thermal conductivities (Table 2). As a result, power devices based on these materials are expected to operate at high frequencies with high power density and efficiency, while also being able to withstand large voltages and currents.

GaN-based devices are the best choice for high-frequency operation, but progress in this area has been hampered by the lack of a suitable substrate technology. The most common approach today is to grow GaN device structures on wafers made from SiC, although cost and reliability issues still remain. For example, 3-in semi-insulating SiC substrates are now commercially available for about US$700 each, compared with less than US$10 for 6-in GaAs wafers. Efforts are also continuing to prevent the formation of so-called micropipes during crystal growth, which reduce the usable area of the wafer and so decrease device yields.

Most work on GaN devices has focused on AlGaN/GaN HEMTs, which typically offer channel-current densities some 2.5 times greater that that achieved in today's GaAs and InP transistors. The fastest reported devices have a gate length of 12 μm and achieve F_t values of 121 GHz and $F_{\max}$ of 162 GHz [4]. For a less aggressive gate length of 0.25 μm, F_t of 40 GHz and $F_{\max}$ of 80–100 GHz are quite achievable. The breakdown voltages for these 0.25-μm devices are typically 70–80 V, more than ten times greater than the breakdown voltage for an equivalent GaAs device [5]. The power densities from these devices can be up to an order of magnitude higher than for GaAs pHEMTs (Figure 4).

Most GaN results to date have been measured on discrete devices, and the development of a GaN MMIC technology remains at an early stage. However, several groups have built GaN MMICs that show promising performance. In particular, researchers at HRL Laboratories in the United States have demonstrated the first GaN power amplifiers to operate at mm-wave frequencies. A single-stage amplifier exploits coplanar waveguide technology and four GaN HFETs with a total gate width of 2 × 100 μm, and achieves a gain peak of 8 dB at 33 GHz with a bandwidth of 4 GHz.

Given the relative immaturity of GaN MMIC processes, it is not surprising that standard GaN MMIC foundry services are not yet commercially available. However, Cree does offer prototyping services on 3-in SiC wafers for research groups wanting to test the performance of the technology, although the U.S. State Department currently restricts the use of this technology to domestic companies.

Cost Factors

Alongside these innovations in device performance, work is continuing to reduce both the size and cost of mm-wave MMIC solutions. By far the best way to make cheaper devices is to reduce the chip area, since the quantity of GaAs used is a major cost driver—particularly once volumes start to increase.

However, MMIC circuit design at frequencies beyond about 50 GHz remains a major challenge. As the operating frequency increases, the electromagnetic design problem becomes more complex, requiring more detailed and accurate simulation techniques to optimize the MMIC's performance. Initial designs are now starting to emerge, but circuit designers are still working to reduce the size—and therefore the cost—of mm-wave MMICs.

Nevertheless, the foundries claim that they could introduce price structures that would allow cost reduction for higher volume orders, even with existing designs. That's because the costs associated with MMIC manufacture are heavily loaded towards the investment needed to set up a fabrication run. If only small quantities of MMICs are ordered, all those set-up costs must be absorbed by charging high unit prices. The higher the volumes, the more the unit cost can be reduced.

The big question, then, is: what is holding back those bulk orders? For most applications, the issue is one of packaging, with mm-wave transceivers often costing about five to six times more than bare MMIC die. Only by reducing the packaging costs can the mm-wave community hope to achieve high-volume sales of MMIC devices and transceivers.

Meeting the Packaging Challenge

To tackle this issue, package designers are now investigating whether low-cost, lightweight materials could replace the expensive and bulky milled-metal packages that have traditionally been exploited for mm-wave components. Most attention is focusing on laminates and low-temperature co-fired ceramic (LTCC) materials, which have already been exploited in MMIC technology at lower frequencies.

LTCC ceramic materials are based on lead-boron-silicon-oxide glass with alumina fillers. The packages are constructed from thin, pliable films of ceramic in the "green," or unfired state. Metal lines are deposited on each layer, usually with thick-film processing technology, and via holes are drilled or punched to enable interlayer interconnects. After all the layers have been fabricated, the unfired pieces are stacked and aligned, and then laminated together and fired. Firing the dielectric and

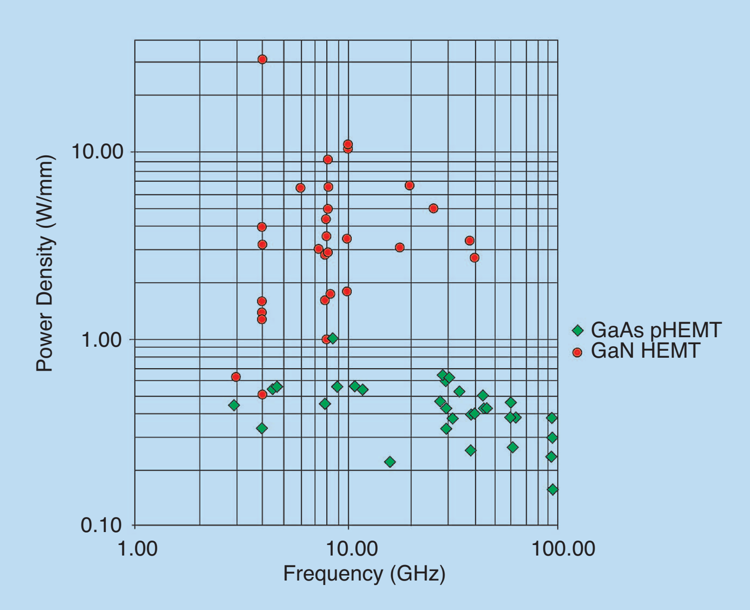

Figure 4. *The power densities recorded for GaN HEMTs are far superior to those for GaAs pHEMTs. (Source: Commercial Applications of Millimetre-Wave MMICs).*

conductor at the same time requires many fewer firing steps than the more conventional thick-film process.

One of the main problems with LTCC packages is that the green ceramic layers shrink during the firing step, typically by 12–16% horizontally and slightly more in the vertical direction. The amount of shrinkage also varies with the number and position of via holes cut into each layer, as well as the metallization applied to the substrate surfaces. However, the use of well-controlled processes enables the shrinkage to be kept within a narrow window, provided the metal loading is balanced across the layers. Some manufacturers are also developing zero-shrink LTCC processes.

Packages based on LTCC materials offer several advantages for MMIC technology: they are light, they can be mass produced at low cost, and they enable signal distribution lines and feedthroughs to be integrated into the package. But perhaps most important is their ability to be formed into multilayer packages that can replace a number of individual modules with a common substrate incorporating both passive components and active devices. This approach reduces the overall size of the MMIC subsystem, minimizes parasitic losses caused by electrical interconnections, lowers assembly costs, and enables high-level integration of functions demanding different device technologies.

For example, Kenjiro Nishikawa and colleagues at NTT have exploited this type of multilayer approach to develop a fully-integrated transmitter operating at 57–60 GHz and requiring a chip area of just 2.89 mm^2. The same group has also built an integrated receiver measuring 5.04 mm^2 and achieving a noise figure of less than 6 dB [6].

To build these compact devices, Nishikawa and colleagues formed a three-dimensional (3-D) interconnection layer—consisting of four layers of 0.25 μm-thick polyimide film and 1 μm-thick metal (0.2 μm for the top-level metal)—on top of UMS's commercial 0.15 μm pHEMT process technology (Figure 5). Once the process is complete,

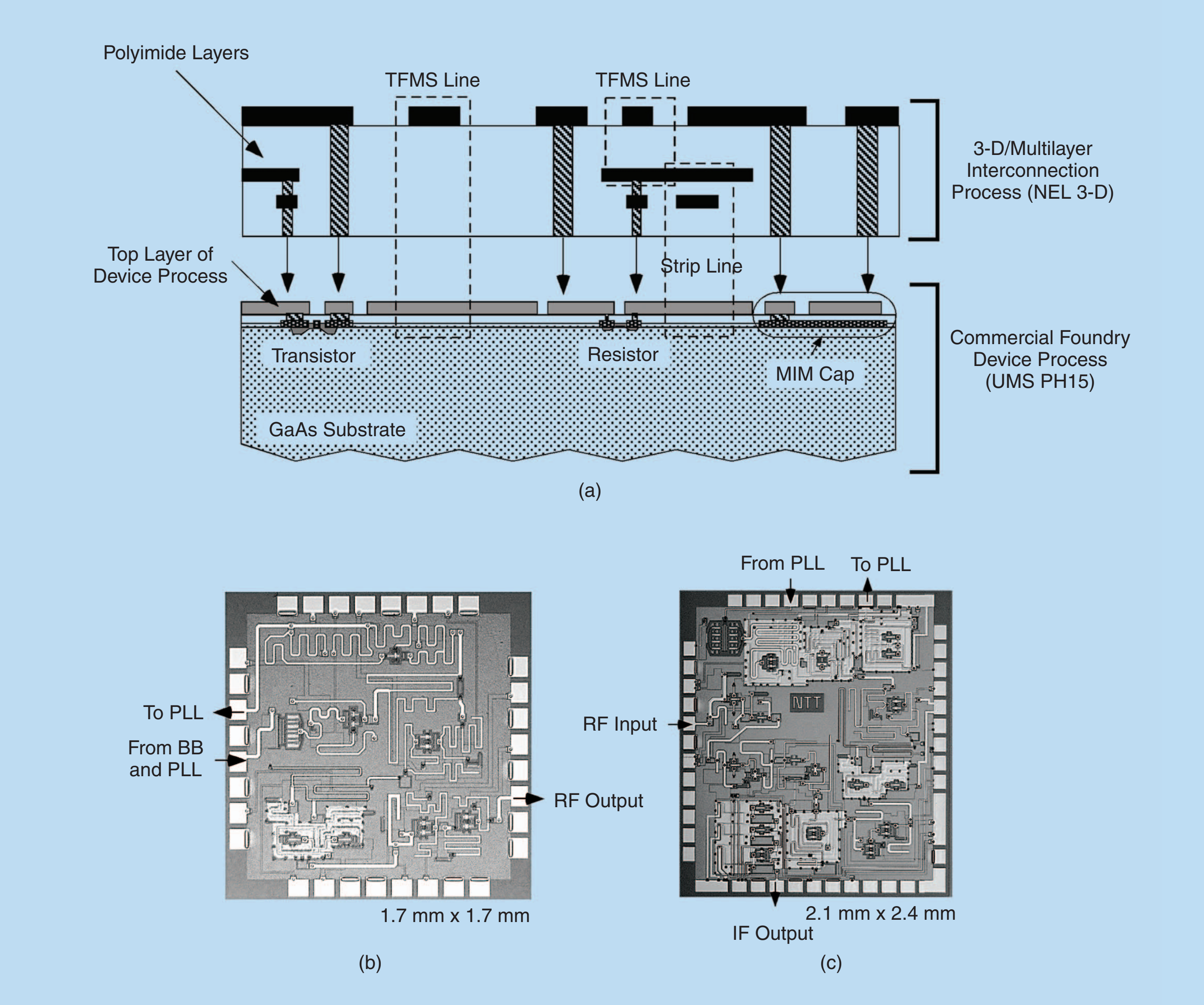

Figure 5. *(a) NTT has produced fully integrated transceivers by combining a commercial foundry process with 3-D interconnection techniques. (b) and (c) show photographs of the transmitter and receiver MMICs.*

the pHEMT achieves a cut-off frequency of 110 GHz.

This type of integration alleviates many of the headaches associated with interconnecting mm-wave components, since traditional wire bonds lead to high parasitic reactances at these frequencies and often require labor-intensive assembly techniques. In contrast, multifunction modules enable low-loss interconnects to be made between the devices and the package as part of the fabrication process.

However, connecting the package to the next-level subsystem remains a major problem. One of the most promising solutions is flip-chip bonding, which allows low-loss interconnects to be achieved with automated pick-and-place machines that also ensure high throughputs and yield.

For example, researchers at NEC in Japan have combined flip-chip bonding with an LTCC multilayer package to build 60-GHz MMIC modules for wireless applications [7]. Fujitsu of Japan, now part of Eudyna Devices, has also indicated that flip-chip modules might be used for automotive radar systems, while fellow Japanese companies Matsushita and NTT are investigating the potential of the technology for high-performance packages.

Other promising interconnect technologies include ball-grid arrays, which exploit an array of small metallic balls to provide a reliable and low-cost interconnect between a ceramic package and a circuit board. Meanwhile, UMS is using coupled electromagnetic transitions between the chip and the substrate to provide W-band interconnects in a module designed for automotive radar at 77 GHz [8]. Kyocera is also marketing an electromagnetically-coupled module aimed at automotive applications.

Raising the Profile

These developments are certainly promising, but more work is needed to introduce standard packaging solutions that are compatible with high-volume manufacturing techniques. The availability of such packaged components would have significant benefits for both commercial end-users and MMIC suppliers. It would reduce operating costs for the customers, since it eliminates the need for clean-room facilities, precision assembly tools and, perhaps most importantly, a team of skilled operators and technicians to mate the MMIC with the package. For MMIC manufacturers, supplying packaged components allows for higher yields, improved reliability, easy handling and, above all, the high throughputs that are possible with high-volume manufacturing processes.

Although the benefits are clear, the solution is less easy to identify. One problem is that most module makers are aligned with their end-user market sectors, which reduces the opportunity for transferring new ideas between subsystem manufacturers serving different markets. It also contributes to a general lack of appreciation among the end-user community of the importance of packaging for achieving low-cost MMIC solutions. Raising the profile of packaging issues along the whole supply chain will be crucial for suppliers to better meet the needs of their customers and, in so doing, reduce unit costs, deliver the required performance and speed up the time-to-market.

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