Today’s Palette of Semiconductor Technologies: A Millimeter-wave MMIC Designer’s Dream

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When I began my career in 1986, the semiconductor choices for RF designers were mostly limited to GaAs MESFET, GaAs HBT, silicon BJT and MOSFET. Monolithic microwave integrated circuits (MMICs) were a new and unproven technology, but their potential launched a wave of startups chasing the emerging phased array radar market. My passion was designing circuits for millimeter-wave frequencies, which led me to InP HBT and GaAs pHEMT. Later, I turned to mHEMT for its low noise performance at millimeter-wave frequencies and SiGe BiCMOS for its capability to integrate multiple functions on-chip.

Looking at the semiconductor landscape almost 40 years later, designers have an abundance of commercially mature processes on their palettes. The challenge is choosing which ones are best suited for the performance goals and have the maturity—production uniformity, capacity, cost, and reliability—to meet the business case for the system. The millimeter-wave semiconductor landscape remains the most interesting today, reflecting the emergence of new markets driving technology development while, as with any nascent market, imposing challenging cost and production demands.

GaAs pHEMT is the workhorse of the millimeter-wave industry. Its high-frequency performance and availability from multiple foundries running 6 inch wafers put it center stage for millimeter-wave applications. Tailoring the gate structure and epitaxial material enables both low-noise and high-power devices. At mmTron, we have developed Ka-Band LNA MMICs with noise figures below 1.5 dB at 30 GHz and W-band amplifiers with more than 1 W of saturated power, designed using commercially available processes. GaAs pHEMTs are also commonly used for linear, nonlinear, and switching circuit elements in millimeter-wave attenuators, switches, phase shifters, and mixers.

In addition to the traditional depletion-mode device, some foundries can process enhancement-mode pHEMTs. These devices don't require a negative gate bias, simplifying bias sequencing, and they enable the integration of modest levels of digital circuitry for control and logic. While most of the focus has been on low to medium frequencies, I anticipate foundries will release enhancement-mode devices with improved millimeter-wave performance.

While lower frequency pHEMTs use optical lithography, e-beam lithography dominates T-gate fabrication for applications above 20 GHz. The most mature commercially available processes have 100 nm gates that support good power and noise performance up to 100 GHz. For pHEMT to support applications above 100 GHz, the gate length must be reduced. The R&D literature reports gates as low as 10 nm, although nothing this small has been qualified for production. As gate lengths continue to shrink, I expect newer lithography techniques with much higher production throughput to be developed that will reduce the cost of millimeter-wave MMICs with gate lengths under 100 nm.

Above 100 GHz, mHEMT is an attractive alternative to pHEMT, particularly to achieve low noise at sub-terahertz frequencies. mHEMTs use InP-based materials fabricated on lower-cost GaAs substrates, tapping the higher electron velocity of InP-based materials. Commercial mHEMT processes offer devices with 35 to 70 nm gate lengths that achieve outstanding noise performance above 100 GHz.

GaN is the newest compound semiconductor technology to enter the millimeter-wave frontier. With its high power density and power-added efficiency, GaN-on-SiC has been widely adopted for power amplifiers because of its proven performance and broad availability, mostly on 4 inch wafers. Our motivation at mmTron is to offer customers the highest linearity MMIC PAs for millimeter-wave applications, so we've added another requirement for GaN.

We have modeled and designed with most of the available GaN on SiC processes in our search for superior linearity, plus power and efficiency. Some lack sufficient gain at millimeter-wave frequencies, and some have excellent power-added efficiency but lack the desired AM-to-AM and AM-to-PM characteristics. By customizing the epitaxial material and tailoring the process, we have optimized foundry processes to achieve the best overall power, linearity, and efficiency.

Combining this customized process with design techniques that optimize device linearity, efficiency, and output power makes GaN-on-SiC our preferred platform for linear amplifiers operating up to 60 GHz.

To support growing market demand, GaN-on-SiC processes must be available from multiple foundries, and the industry will need to move from 4 to 6 inch wafers, significantly reducing device cost. GaN gate lengths will likely follow a similar path as pHEMT, and, in time, I expect GaN will support millimeter-wave amplifiers operating higher than 100 GHz. With the increasing demand for higher power and efficiency, we will also see a cost reduction in SiC substrates and fabrication processes.

GaN-on-Si has received a lot of press and significant investment from the government, microwave, and silicon communities, aiming to combine the performance advantages of GaN with the high-volume capacity of silicon wafer fabs. Currently, GaN-on-Si processes are less mature than GaN-on-SiC and are only available from one or two foundries with limited external access.

Over the next decade, I foresee the introduction of exotic device structures that will make GaN-on-Si attractive for higher volume applications such as smartphones. In addition to a proven, repeatable GaN-on-Si process, wide adoption will require these platforms to be available from multiple foundries and widely accessible by designers (e.g., fabless startups).

For decades, the compound semiconductor industry claimed the millimeter-wave spectrum for itself, safe from silicon encroachment. While the first wave of silicon targeting 802.11ad Wi-Fi at 60 GHz did not achieve the desired adoption, silicon-based automotive radar at 77 GHz has secured a beachhead and is widely available as a safety feature in new cars. The licensing of millimeter-wave bands for 5G (designated FR2) led to the development of active phased arrays using SiGe or RF CMOS transceivers for the radio access network. These transceiver ICs integrate the transmit and receive functions (low-noise amplifier, power amplifier, switch, variable gain amplifier, and phase shifter), multiple channels (4, 8, or 16), control circuitry (SPI), and auto-calibration and temperature compensation.

Silicon processes are always attractive for applications that demand low cost, high volume, and high integration. Today, it’s the only logical choice for the millimeter-wave transceiver in the 5G mobile phone. For the active phased arrays in the network, however, silicon RFICs have drawbacks, power and linearity that limit the range and data rate of the radio link. To compensate, the network requires larger antenna arrays and more repeaters. Compound semiconductor solutions remain better suited for higher power, extended-reach applications, as they allow for smaller antennas and longer link distances. To illustrate the point, mmTron’s

TMC211 single-chip GaN amplifier provides 23 W of output power at a 19 dB noise power ratio. A silicon-based amplifier with the same linearity has an output power only of tens of milliwatts.

Every technology has its advantages and shortfalls. As I noted earlier, the challenge is choosing which is best suited for the performance goals and supports the business case for the system. As millimeter-wave 5G and satcom systems evolve through successive generations, we’ll see networks using silicon and III-V ICs to achieve the optimum network performance that will improve with each generation. After almost 40 years, I find this the most fulfilling time to be working in millimeter-wave. No longer relegated to lab or niche applications, our pallet of millimeter-wave semiconductor technologies is truly enabling global communications.