Development of E-pHEMT Technology

White Paper

Avago's E-pHEMT technology

E-pHEMT (enhancement-mode high-electron mobility transistor) is a semiconductor process optimized for wireless applications that operates from a single positive voltage source. Ordinary depletion-mode pHEMTs conduct at zero gate bias, or when the drain current, Id, reaches a saturated level (Idss) at a gate-source voltage (Vgs) of 0 VDC. An E-pHEMT shows no conduction at zero gate bias, so that Id = 0 at Vgs = 0 V. Thus, it can operate without the negative voltage (required for switch on) required for depletionmode devices. Other gallium arsenide metalsemiconductor field effect transistors (GaAs MESFET—also simply called GaAs FETs) and high-electron-mobility transistors (HEMT) also operate from a positive voltage supply and require a negative voltage to turn on. The added components required to provide the negative voltage increase system cost, take up valuable board space and require extra design effort.

Evolution of E-pHEMT technology at Avago

Avago developed its first E-pHEMT devices in the 1980s at what was HP Labs (now Avago Labs) in Palo Alto, California, with the initial motivation being to develop ICs for digital signal processing. For that application, individual transistors had to be small and tightly fitted in the IC layout. The average gate periphery of a transistor was 100 microns and the emphasis was on threshold voltage uniformity of less than 30 mV. Leakage current was of less concern for integration levels of 2,000 transistors, a worthy goal at the time for GaAs.

Today, in contrast, developmental poweramplifier ICs for handheld devices are using E-pHEMT output driver transistors with 20-mm total gate periphery, a 100-times increase in individual device size. Concurrently the leakage current at quiescence has decreased to less than 0.5 µA/mm to prolong battery re-charge intervals.

Avago has manufactured and sold PHEMT (pseudomorphic high-electron-mobility) products since 1988, with PHEMT products dominating Avago's GaAs fab output for the last ten years. In 1994, transfer of an enhancement-mode version of PHEMT technology from Avago Labs was initiated. In 1997, based on the success of the technology, the decision was made to organize design and wafer fabrication teams to address E-pHEMT exclusively at Avago's Santa Clara wafer fabrication location. During the last four years, Avago has focused its epitaxial and wafer development talents and resource on the fabrication of four-inch PHEMT wafers. This is in contrast to other companies where E-pHEMT was only one of two or three candidates for potential use in cellular handset power amplifiers.

The necessary combination of low cost, large device size, high uniformity, high power, and high efficiency makes extraordinary demands on the quality of the epitaxial wafer growth methods and wafer processing technology. Although several semiconductor companies have announced E-pHEMT capabilities, few of these devices operate in a true enhancement mode that totally eliminates the need for negative-polarity supplies. Others have the RF performance but not the low leakage needed for battery life, or vice versa.

Epitaxial wafer technology

To reduce wafer-processing cost, wafer size has to be increased. For Avago, this meant an upgrade from 3-inch to 4-inch wafers in the Santa Clara fab, and in short order to 6-inch in a new facility in Ft. Collins, CO. Molecular-beam epitaxy (MBE) reactors for multiple 4-inch wafer growth have only been available in routine production for 31/2 years. Because E-pHEMT threshold sensitivity depends on a number of epitaxial growth parameters, both the in-situ monitoring as well as the post-growth wafer characterization methodologies for production had to be developed quickly. The learning curve is steep, and because of the rapid equipment upgrade interval, there is little room to catch one's breath before moving on to the next machine. Equipment for 6-inch MBE wafer growth is just coming on line. For wafer characterization, instrument vendors have only started within the past year to ship cassette-to-cassette GaAs wafer characterization equipment such as PL (Photoluminescence) and X-ray. Reliable, accurate, automated epitaxial wafer analysis software for III-V semiconductor wafers has had a similarly recent start in life. Against this background, although claims by a number of manufacturers have been made for E-pHEMT in production, the knowledge base for large epitaxial wafer production is fairly new.

The control of layer thickness and composition, along with epitaxial production techniques have been advanced significantly at Avago. Typically E-pHEMT requires a higher degree of control in some aspects of epitaxy than HBTs due to the multiple thin layers needed for its high current and low leakage performance.

Wafer processing

Good control of the threshold current, Imax, and leakage current depends on process control of the Schottky gate contact. Since E-pHEMT is a surface-channel device, surface properties are critically important–especially since III-V material has no native oxide for protection. Any surface residues change the transistor threshold and leakage. For example, too much aqueous cleaning easily erodes the surface layer, resulting in low I_{max} and low threshold voltage. Plasma bombardment during etching and ashing can decrease channel current and increase leakage.

For small digital transistors, threshold uniformity can be achieved with some trade-off of other device parameters. However, for cellular PA transistors, the simultaneous achievement of low leakage and high I_{max} in a specified threshold voltage range is essential. In this context, the etching, cleaning, and protection of the III-V wafer, and the gate electrode formation sequence constitute a proprietary process the Avago considers critical to the success of its E-pHEMT technology.

GaAs IC fabrication equipment with standard recipes is just coming on line. Previously the GaAs market was too small to sustain any significant development effort on the part of equipment vendors. As a result, each GaAs IC manufacturer had its own proprietary process modules on a particular set of process equipment. The composition of the equipment set differed from manufacturer to manufacturer. Without a common set of metrics to calibrate the different brands of equipment, duplication of a process was not easy.

Device and circuit interaction

The rapid advancement of silicon ICs in performance and density benefited greatly from the availability of device/circuit modeling and simulation software. The same has not been true very dependent on individual device structures and the parasitic circuit equivalents. The need for a large dynamic range of operation in a power amplifier is an additional requirement. Small signal models can be made to work reasonably well for low noise GaAs amplifier design– for power amplifiers, though, large-signal models are needed for simulation but often are lacking and at best inadequate, even in the case of silicon power devices.

Without a valid device model and circuit simulation, many E-pHEMT model parameters can only be obtained empirically over multiple iterations. Hence, the device and its circuit develop symbiotically, each feeding the other the needed information over a number of design cycles. Even at the end, some small adjustments can be made to enhance the overall performance. At Avago we have been keenly aware of this symbiotic development of device and circuitry. Therefore the design and the fab teams have been co-located in the same facilities from the start of the E-pHEMT project.

Conclusion

The development of III-V E-pHEMT power amplifiers can be likened to a race to get to a seldom-traveled location in the world specified only by longitude and latitude, in the shortest time. The destination is specified but the starting point of each competitor is different, and the means of transportation are unrestricted. How one gets to the destination depends on the starting point, the routes and detours taken, the information obtained along the way, and the opportunities and breaks that one makes use of. Avago has struck out on an E-pHEMT path that is leading rapidly toward the finish line.

For product information and a complete list of distributors, please go to our web site: **www.avagotech.com**

5988-4965EN - June 8, 2007