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Silicon Germanium Hetrojunction Bipolar Transistor Amplifiers Replace Gallium Arsenide for Wireless and Broadband Applications

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While the cellular handset market is experiencing growth, service providers and consumers expect low-cost handsets. Handset complexity and features have grown significantly while maintaining the expectation for lower cost. Traditionally, reducing cost in electronics subsystems and modules has been achieved by leveraging low-cost CMOS silicon processes to integrate as many discrete devices as possible. However, in the case of the radio frequency (RF) front-end radio modules found in all wireless systems, the need for discrete and exotic gallium arsenide (GaAs) devices in radio subsystems has limited the ability to reduce cost. Presently, the integration of a radio in a cell phone on a single piece of silicon is possible by integrating the transceiver, antenna switch, power amplifier (PA) and power controllers, eliminating the need for expensive discrete GaAs devices.

A silicon-on-insulator (SOI) option, available on processes such as 0.18-micron RF CMOS and 0.18-micron silicon germanium (SiGe) BiCMOS, enables the integration of the antenna switch with the PA into one die. This technology promises to deliver higher levels of integration for future mobile devices, wireless local area networks (WLANs) and WiMAX systems while displacing chips built today in more expensive GaAs processes, reducing die costs up to 50%.

One key area of cost reduction in a radio platform is the PA. SiGe heterojunction bipolar transistor (HBT) amplifiers provide an alternative to present GaAs-based amplifiers. Current handset PAs are dominated by GaAs/ aluminum gallium arsenide (AlGaAs)/ indium gallium arsenide (InGaP) HBT amplifiers. These were introduced to replace earlier generations of metal semiconductor field-effect transistor (MESFET) amplifiers based on discrete and integrated designs. Newer wireless protocols such as wideband code division multiple access (WCDMA), universal mobile telecommunications system (UMTS), 802.11n and WiMAX are increasing in complexity and power requirements. In addition, multiple connectivity protocols are being integrated into a single solution that includes cellular, Wi-Fi and Bluetooth, thereby increasing the number of radios and hence PAs. While the performance of GaAs amplifiers is adequate, the additional cost and space of these amplifiers in new mobile devices is undesirable to today's designers and mobile solution vendors. This article explores aspects of the performance, size and cost of SiGe HBT amplifiers within a wireless transceiver.

Cost

Silicon-based wafers and processing technology are less expensive than GaAs-based wafers due to the reduced cost of substrate material and processing tools. Wafers used in silicon-based processes are 8 inches in diameter versus 6 inches for GaAs wafers, thus yielding almost two times more die per wafer. When comparing GaAs- and SiGe-based PAs, the overall die size is comparable, hence the lower cost for a SiGe-based amplifier. In general, module cost is estimated to be about 20% less.

Active Device Performance

Pivotal to the success of any amplifier design is the active device capability. N-type/p-type/n-type (NPN) device performance is based on several factors: process technology doping profiles, structure and physical layout.

Breakdown

There are several factors that contribute to the breakdown of a transistor such as Zener, punch-through and avalanche breakdown. Common-base and common-emitter breakdown are measured in common-base configuration with base open (BV_{cbo}) and in common-emitter configuration with base open (BV_{ceo}). RF transistors can be designed to withstand RF power reflected from the antenna. This reflected energy is also known as voltage standing-wave ratio (specified as ruggedness). SiGe process technologies targeting amplifiers can provide breakdowns ranging from 6V BV_{ceo} to 8V BV_{ceo} . The higher breakdown devices are less prone to fail when subjected to large power reflections.

Cutoff Frequency

The cutoff frequency (F_t) of a bipolar transistor is the frequency at which the transistor's gain drops to unity and thus is longer able to amplify. The effective bandwidth of an amplifier for circuit design is an F_t 10 times the band of operation. Although the transition frequency of SiGe NPNs can range from 33GHz to 80GHz, it is a tradeoff with breakdown. A typical F_t for a SiGe PA is 38GHz.

Beta

Beta is commonly known as the current gain of a bipolar transistor and is given as the ratio of the collector current relative to the base current. This current gain is heavily dependent on the doping concentrations in the emitter and base. For example, a SiGe NPN transistor fabricated on a 0.18-micron SiGe BiCMOS process ranges in beta from 100 to 140.

Biassing

Present biasing techniques used in GaAs HBT linear amplifiers are based on current mirrors requiring reference voltages to be generated externally to supply a biasing transistor with a V_{be} of $\sim 1.2V$, unlike SiGe transistors which require $\sim 0.76V$. The elimination of any external circuitry used for the reference voltage simplifies current mirror designs and allows the integration of logic into the amplifier, further reducing the external circuitry of the turn-on/off circuits.

Thermal Rise

Thermal rise within an active device can impact performance significantly and be controlled through appropriate layout techniques and metallization. An optimized layout can affect the thermal rise within a device. Analytic computation of temperature fields by the source (device emitter) is used to optimize the layout. A device can deliver additional power with an optimized layout while maintaining low-temperature rise per unit of power.

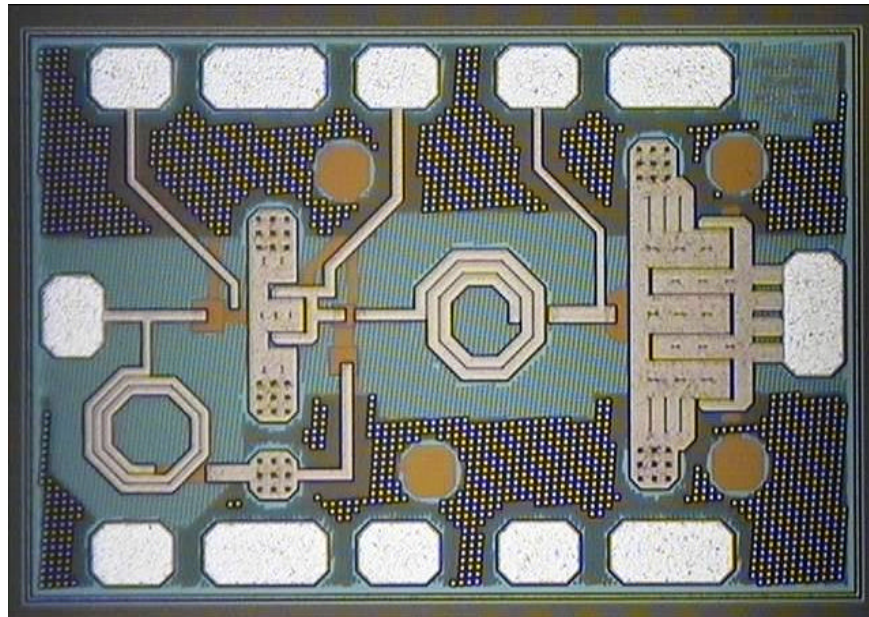
Stability

Amplifiers require the unconditional stability of transistor cells, which can be achieved using ballasting techniques. When comparing transistors that incorporate ballasting at the base and the emitter, it was concluded by simulation that emitter ballasting did not contribute significantly to stability, but that base ballasting was most effective. Generally, base ballasting is required for large power transistor cells.

Through Wafer Via

Another important factor is the through-wafer via (TWV), which provides an emitter with short lead inductance by connecting directly to the ground, reducing the inductance of bond pads and bond wires. The application of traditional TWV process technology is generally done on the backside of a wafer by tunneling a copper post. By eliminating some bond pads and bond wire contacts, the overall die size of an amplifier can be reduced by 15% to 20%. An additional benefit of vias is they provide a thermal dissipation pipe, allowing stable operation at extremes. Figure 1 shows a layout of a two-stage SiGe PA utilizing TWVs.

Figure 1. Two-Stage WCDMA Power Amplifier Driver



Linearity

One of the most critical performance criteria of an amplifier is efficiency. As the battery drains, it impacts talk time. This is undesirable, as it degrades the user experience for consumers and reduces revenue per user for service providers. In addition, data-heavy protocols, such as WCDMA, require an efficiency premium due to linearity requirements. One innovative way to impact talk time is to operate the amplifier in low-power mode when possible. This can be achieved when a cell phone is operating in urban environments, where base stations are likely to be in proximity of the user, thus reducing the need to transmit at full power. Figure 2 compares a silicon-based driver and a best-in-class GaAs WCDMA-based amplifier. Although the comparison is made between a single-stage amplifier and a two-stage cascaded amplifier, it is expected to match the performance of a commercial amplifier despite all the parasitic effects of the additional stage and the package. For high data rate 802.11b/g amplifiers, good linearity and low error vector magnitude (EVM) are required. To obtain sufficient margin for EVM and spectrum mask, the second stage power transistor must have a compression point (P1dB) of at least $\sim 28\text{dBm}$ at 3.3V. At this compression, the compliance of 180-nanometer-based power cells, such as an 802.11a/b/g cascaded amplifier, can be met at 19dBm in "g" mode and 23dBm in "b" mode.

Figure 2. PA Driver Adjacent Channel Power vs. Power-Added Efficiency at Low Power for SiGe and GaAs

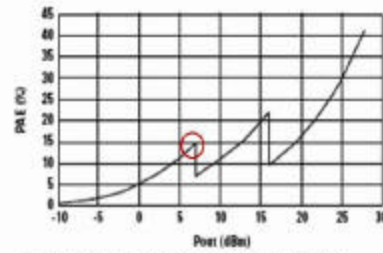
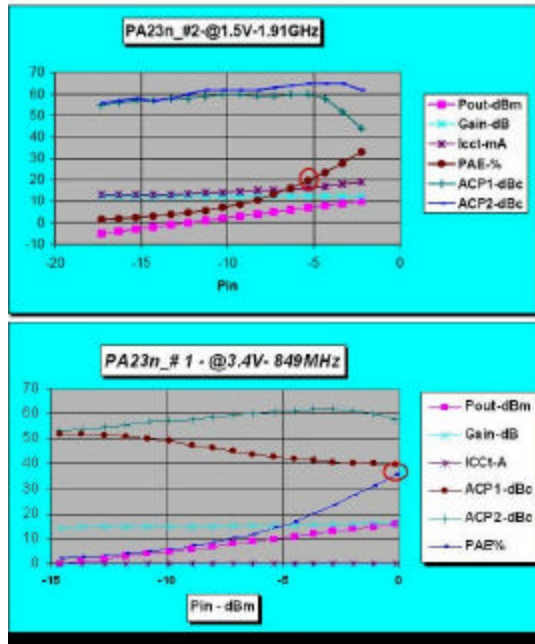


Figure 3. Power Added Efficiency vs. Output Power.

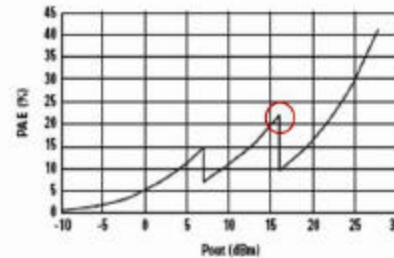


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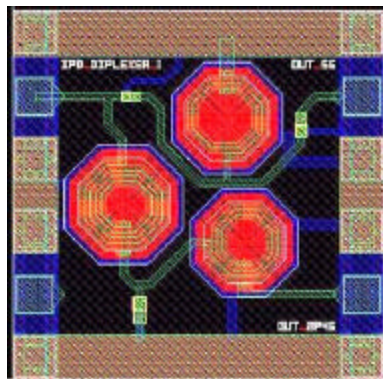
Low Power mode - Higher PAE in a single stage configuration compared to GaAs

Caption: Low-power mode - higher power-added efficiency (PAE) in a single-stage configuration compared to GaAs.

Integration

Integrating a transceiver with a PA further makes SiGe technology attractive in applications such as a WLAN 802.11a/b/n and extended global system for mobile communications (EGSM) front-end modules (FEMs). An integrated passive device's performance in a 0.18-micron SiGe BiCMOS process is comparable to GaAs as well as silicon, enabling harmonic filtering and partial matching on die and incorporating duplexing capability. Figure 3 shows a layout of an integrated Wi-Fi diplexer enabling integration with a PA. The availability of SOI as a variant to SiGe process technologies allows the further integration of FEMs. SOI RF switches provide all the required features for an RF switch: low insertion loss due to reduced parasitic capacitances, high isolation by utilizing trenches, linearity, power handling, low-power harmonics and thermal dissipation.

Figure 3. Integrated Diplexer Layout



While GaAs-based pseudo high electric mobility transistor switches provide adequate performance, their base material comes at a cost premium when compared to silicon-based technologies fabricated on insulating material. The growth of 3G-based phones requires a higher count of poles within the same switch, such as single-pole nine-throw (SP9T), making the switch considerably bigger. Furthermore, the availability of high-breakdown NPN for PAs as well as SOI switches on the same monolithic die is a perfect synergy between the two technologies. For a long time, handset RF module vendors have integrated several dies, each from a different process technology, on a printed circuit board substrate. They have been involved with both design and production – a complex and costly task for a market requiring high performance at low cost.

Generally, EGSM modules contain two integrated passive devices, which serve as harmonic filters. These are generally based on elliptic-lumped element designs. With higher quality factor inductors, insertion losses are further reduced with improved rejection. Integrating the harmonic filters and the PAs with the RF switch completes all functions required for an FEM on one die without compromising performance. The availability of positive-intrinsic-negative (PIN) diodes facilitates the design of control circuits, such as switches and attenuators, which can be in SiGe process technology. PIN diodes are realized by the HBT layers forming a P+ base layer and an N-collector layer isolated by a deep trench, further enhancing the isolation. While PIN diodes are limited to low-power applications, they can be delegated to control functions such as attenuators and phase shifters. Typical insertion loss is below 1dB and isolation in a single-pole double-throw (SPDT) switch is over 40dB. Topologies requiring attenuators can incorporate these switches with unsilicided resistors.

Conclusion

The design of multi-stage amplifiers or FEMs incorporating SiGe process technology meets or exceeds commercial requirements and specifications, while providing an excellent linearity and efficiency tradeoff as well as a significantly reduced die cost. A Wi-Fi 802.11a/b/g PA implemented in this technology can be designed to incorporate all required features, matching the performance of GaAs amplifiers and RF switches. The design of a standalone amplifier or an amplifier integrated with a transceiver provides further flexibility unlike GaAs-based amplifiers. The option of incorporating an RF switch enabled by SOI technology further makes the dream of a true all silicon-based radio front-end a reality.