Kopin bandgap engineering improves HBT performance

High-speed MMICs with lower turn-on voltages can be built by switching GaAs-HBTs for GAIN-HBTs with a dilute nitride base, say **Matt Micci** and **Roger Welser**. The advancement could allow mobile phone designers to build more reliable handsets operating at higher data-rates.

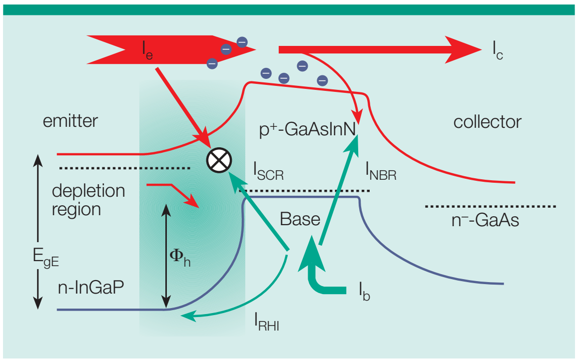
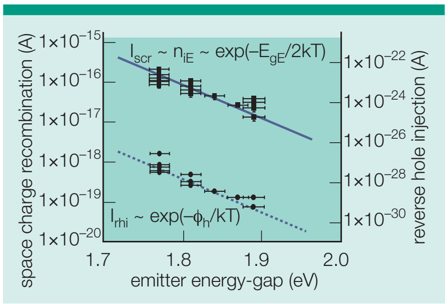


Fig. 1: GAIN-HBT devices consist of a compositionally graded GaAsInN base inserted into an otherwise standard InGaP/GaAs-HBT. The net result enhances collector current (I_c) while minimizing the key base current (I_b) components: neutral base recombination (I_{NBR}), space charge recombination (I_{SCR}), and reverse hole injection (I_{RHI}).



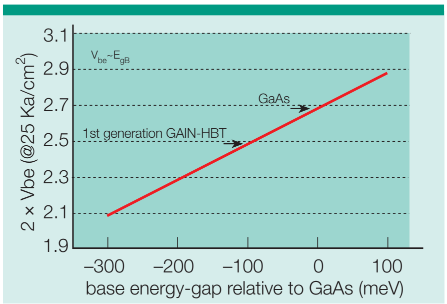


Fig. 2 (left): Increasing the emitter layer energy-gap (E_{gE}) reduces space charge recombination (I_{SCR}) and reverse hole injection (I_{RHI}), improving device reliability and enhancing stability over temperature and bias. Fig. 3 (right): Replacing two GaAs-based HBTs configured in series with two GAIN HBTs reduces operating voltage by 100 meV to 2.5 V, a critical threshold given today's battery technologies and mobile-phone architectures.

During the past decade GaAs heterojunction bipolar transistors (HBTs) have strengthened their position as the technology of choice for fabricating wireless handset power amplifiers (PAs). By 2004, more than 75% of the 650 million mobile phones sold employed GaAs-HBT technology for power amplification. This dominance resulted from several cost and performance factors that enabled GaAs-HBTs to outperform entrenched silicon and competing GaAs-FET technologies for PA designs.

GaAs-based bipolar transistors offered a powerful combination: high linearity and efficiency over a wide frequency range; high breakdown voltage; and single-supply voltage operation. Consequently, PAs built using GaAs-HBTs delivered the RF performance and robustness required for demanding mobile-phone applications. From a manufacturing perspective, several factors have allowed GaAs-HBT PA production costs to be highly competitive: the much smaller MMIC die sizes enabled by the vertical HBT device; extremely high fabrication yields resulting from the larger, easy-to-process device geometries; streamlined quick fabrication processes; and ease of integration. Finally, ongoing bandgap engineering of the material structure has kept GaAs-HBT technology at the industry's leading edge by continually offering cost and performance improvements for PA ICs and modules.

Nobel laureate Herb Kroemer's early vision of wide-bandgap heterojunction structures delivering superior transistor performance is embodied in today's GaAs-based HBTs. The success is partly due to the many advances in material synthesis. For example, improvements to the reliability and performance of HBTs have been delivered through alterations in the emitter layer, most notably the replacement of AlGaAs alloys with InGaP. Still, given the ever-increasing sophistication of emerging wireless products, and the resulting search for improved PA capabilities, new approaches to further enhancing the transistor's performance must be explored.

Bandgap engineering

At Kopin, efforts have been directed at engineering the bandgap of the base layer material – what we call GAIN-HBT technology. Incorporating dilute-nitride alloys into the base layer of the GaAs-HBT lowers the turn-on voltage, as well as enabling implementation of more sophisticated compositionally graded device structures. Recently, we reported results from first-generation GaAsInN-HBT (GAIN-HBT) ICs in pilot production. As predicted, using GAIN-HBT devices in the MMIC reduced turn-on, offset and knee voltages while improving speed performance and circuit stability with temperature and bias. These enhancements were achieved without any changes to our customers' device processing – a truly plug-and-play solution.

The baseline material structure of a GAIN-HBT transistor consists of an InGaP emitter, a graded GaAsInN base, and a GaAs collector (figure 1). This structure incorporates all of the previous improvements to our InGaP/GaAs-HBTs, but further leverages performance through the insertion of a new base layer material. Material properties play a key role in crit-

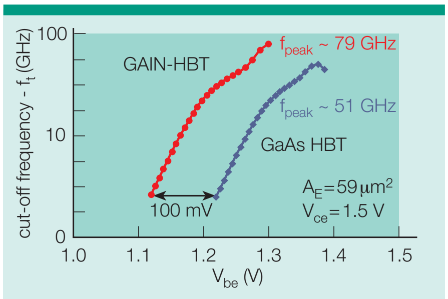


Fig. 4: GAIN-HBT technology can be engineered to enhance RF performance. Here, a 50% better maximum cut-off frequency is achieved in a GAIN-HBT device compared with a standard GaAs-HBT of similar collector structure.

ical HBT device parameters, including the primary base and collector current components depicted in figure 1. The performance advantages of GAIN-HBTs arise from their higher collector current and the suppression of undesirable base current components – neutral base combination (I_{NBR}), space charge recombination (I_{SCR}) and reverse hole injection (I_{RHI}).

The HBTs' wider emitter energy gap suppresses reverse hole injection, thereby enabling higher base doping levels – a key element of HBT performance. This combination means that HBTs can combine high DC gain with low base sheet resistance and short base transit times for increased RF power gain. Much of the early work on GaAs-HBTs was directed at achieving high, stable doping levels in the base, either by using carbon dopants (with their low diffusion coefficients), or by developing techniques that suppress beryllium dopant diffusion. GAIN-HBT devices use very high base doping levels (4–5 × 10^{19} cm^{-3}) produced by special growth techniques that compensate for the tendency of carbon doping to decrease with the addition of indium.

The collector structure of GaAs-HBTs also directly impacts on the transistor's breakdown voltage and microwave power gain. However, the addition of indium and nitrogen to the base layer has no effect on the device parameters typically governed by the collector design. With GAIN-HBT technology, collector thickness and doping can be readily tuned to meet specific RF power and robustness requirements, just as in standard GaAs-HBTs.

Reliability gains

In the early days of GaAs-HBT development, reliability was a concern for the newer, novel devices. However, in time, material engineering increased mean-time-to-failure (MTTF) rates to over 1 million h. This was primarily achieved by optimizing the emitter's layer properties. First, the emitter's thickness and doping were adjusted to ensure the effectiveness of the ledge passivation of emitter material left around the device perimeter.

Once recombination at the surface of the base layer was suppressed with a properly designed emitter ledge, recombination enhanced defect reactions at the emitter–base junction were found to limit device reliability. Emitter properties again played a critical role in improving average MTTF. As larger emitter energy-gaps suppress both the space charge recombination and reverse hole injection components of the base current (figure 2), device reliability was improved through increasing the emitter's energy-gap – typically by using an InGaP emitter.

Device performance also benefited from suppressing the base current with larger emitter energy-gaps, which improved properties such as the stability of the DC characteristics with both bias and temperature. Although InGaP and high aluminum-containing AlGaAs emitter layers both minimize base current, the lower conduction band discontinuity of InGaP can deliver ideal injection efficiency. For this reason, GAIN-HBT structures retain InGaP as the emitter material.

Next-generation, feature-rich cellular phones will continue to demand greater performance and robustness due to increased data-rates and duty cycle requirements. While

GAIN-HBTs combine plug-and-play with excellent reliability

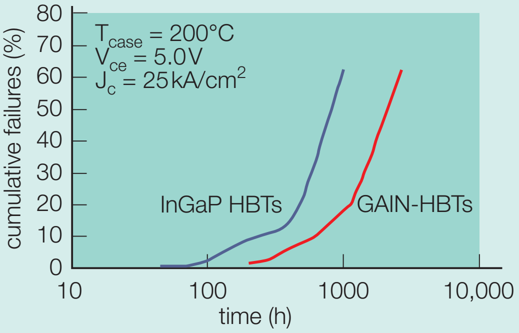


Fig. 5: GAIN-HBT structures offer excellent reliability. Accelerated ageing tests reveal that under typical operating conditions the lifetime of these devices exceeds that of GaInP/GaAs devices, at more than 1 million h.

New technology often faces formidable barriers to its adoption into high-volume products. In addition, circuit and process development costs, and reliability concerns, can derail even the most promising of technologies. However, the properties of GAIN-HBT devices can help reduce these barriers to entry and allow a smoother path through customers' arduous platform qualification procedures.

One advantage of GAIN-HBT technology is that it is built upon existing GaAs epitaxial and integrated-circuit fabrication processes. GAIN-HBT MMICs can be processed alongside conventional GaAs-HBT circuits, using identical etches, metallization and circuit designs. Consequently, GAIN-HBT devices can be inserted into established circuit products for enhanced performance.

GAIN-HBT devices are also intrinsically more reliable. This was recently demonstrated by the technical teams at Skyworks. In a presentation at the 2005 MANTECH Conference, GAIN-HBT devices exhibited MTTFs exceeding standard InGaP/GaAs-HBTs (figure 5). These results fulfilled expectations based upon the current understanding of GaAs-HBT reliability physics. The increased difference in energy-gap between the base and emitter layers in GAIN-HBT structures is expected to reduce recombination currents at the base–emitter junction, and lower the recombination-enhanced defect reactions that limit GaAs-HBT reliability.

With proven gains in baseline device performance, high reliability and straightforward implementation, GAIN-HBT technology offers an effective, practical roadmap for the GaAs-HBT community. We anticipate a revolutionary impact on the design of wireless power amplifiers and high-speed digital integrated circuits currently employing GaAs-based HBTs, including lower-voltage operation, reduced power consumption, improved linearity characteristics and higher-speed operation.

modifications to the emitter and collector have helped enhance GaAs-HBT performance, even greater improvements can be produced by bandgap engineering of the base layer. Kopin's GAIN-HBT technology offers a greater level of design freedom by utilizing dilute nitride GaAsInN alloys to enhance the various device characteristics that are governed by base-layer properties.

One key parameter is the transistor's turn-on voltage. GaAs' relatively large energy-gap leads to a fairly high turn-on voltage (~1.35 V @25 kA/cm^2). When two transistors are stacked together – which is a common configuration for PA control circuitry – the minimum voltage required to operate the circuit is fundamentally constrained by the GaAs base layer. Previously, lower energy-gap materials lattice-matched to GaAs have not been available to address this issue. However, nitrogen-containing III-V alloys are known to have unique bandgap-bowing properties, enabling the growth of reduced energy-gap materials that can be lattice-matched or strain-minimized to GaAs. Just a modest 100 mV reduction in the base-layer energy gap can extend the minimum operating voltage below 2.5 V for GaAs-HBT PAs (figure 3).

The higher collector current resulting from a lower-bandgap base material alters the ratio of collector and base current components (figure 1) in ways that improve transistor stability and efficiency. Researchers at Virginia Tech, VA, and elsewhere have shown that the DC characteristics of GAIN-HBT devices are stable from 50 to 200 °C. Because GAIN-HBT devices use a lower energy-gap material in the base, they are really double heterojunction structures. Such structures have additional device performance benefits, but extra care is needed to suppress barriers to electron flow at base–emitter and base–collector junctions, as is routinely done for high-speed, higher-cost InP-based devices. GAIN-HBT devices also possess the expected lower offset voltages required to bring the bipolar transistor out of saturation, which can be used to improve the RF power efficiency of amplifier circuits.

Perhaps GAIN-HBT technology's most exciting feature is its use of sophisticated base-layer structures. True bandgap engineering is achieved through the incorporation of compositional grading across the base layer. The resulting built-in quasi-electric field accelerates electrons through the base, lowering the overall transit time. Improved electron transport enhances several fundamental device properties. Peak current gain is increased in devices employing compositional grading due to a reduction in neutral base recombination. At the same time, microwave performance is improved through a cut in base transit time (figure 4). This ability to simultaneously enhance DC and RF properties equips device and circuit designers with new tools to optimize GaAs-based PA performance. ●

Further reading

L Rushing *et al.* 2005 *CS MANTECH Digest* p57.
B Dickerson *et al.* 2003 *GaAs MANTECH Digest* p295.
R E Welser *et al.* 2000 *IEEE Electron Device Lett.* **21** 196.

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