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In the last issue the overview was more of a retrospective, this time it showcases some of the exciting III-V-related device technologies in prospect, such as improved HBTs.

Amongst more intriguing longer-term prospects are magnetic materials nanowiskers, and new formats for existing devices such as 'electronic skins'.

Into the 2005 crystal ball

The annual IEDM meeting has always been a useful barometer - the 2004 meeting which celebrated the half-century, naturally included some major new developments. This article will, however, not be restricted to the IEDM but take a broader view so as to try to better reflect progress in the compounds. The IEDM concentrates on silicon-related devices but because some of the best performance can only be achieved in III-Vs, the record-breakers are often in GaAs and the like.

For example, T Hussain *et al*, at HRL Laboratories described a device combining speed with the lowest power consumption ever reported for an HBT: 430GHz (f_{max}) and 370 GHz (f_t) using only 6mA of current. HRL said the emitter widths are the smallest of any III-V devices reported to date (less than 250nm wide) hence the impressive power efficiency. They expect to be able to further reduce base resistance by 50% to give f_{max} of 500 GHz.

Figure 1: Micrograph of a 3-W power SiGe HBT module, consisting of 160 emitter fingers with $0.9 \times 30.3 \mu\text{m}^2$ emitter area each

Impressive device performance is reliant not only on the semiconductor, but also on the packaging materials. One group's work can be taken as an example of the importance of having a

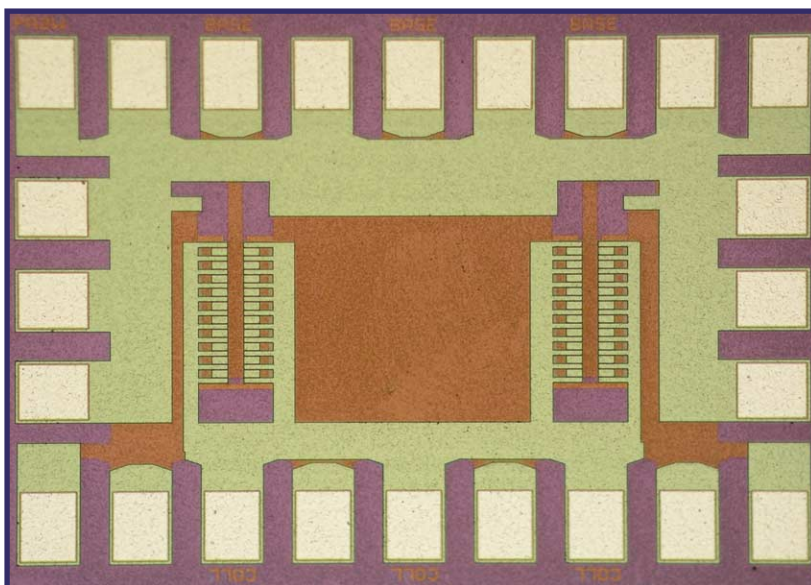
package with low thermal resistance mounting - in this case by an in-house developed flip-chip soldering process on diamond or AlN submounts. A flip-chip mounted 26V GaInP/GaAs power HBT was reported by P Kurpas, *et al*, of the Ferdinand-Braun-Institut fuer Hoehstfrequenztechnik (FBH) in Berlin in conjunction with United Monolithic Semiconductors. Their high-voltage HBT power cells deliver up to 14W at 2 GHz with a PAE up to 71% and high gain of 14dB.

Compare this to some of the benchmarks being set in SiGe! 2005 will no doubt see these moved even higher. IBM's M Khater *et al*, have reduced the emitter width in their SiGe HBTs by reducing the spacing between the base and emitter. In so doing they lifted f_{max} and f_t to 340 GHz and 300 GHz, respectively, at a 1.7V breakdown voltage.

Power output importance

Of course power output is also important; 3W RF power with concurrent 67% PAE and power gain of 9.8dB has been achieved from 0.9 μm emitter finger power SiGe HBTs. This translates to an RF power density of 1.13 mW/ μm^2 . The work was reported in new papers from Assistant Prof Zhenqiang Ma and his colleagues at the Dept of Electrical and Computer Engineering, University of Wisconsin, in conjunction with Jazz Semiconductor. These were developed using Jazz Semiconductor's 4-metal SiGe BiCMOS platform for 1.9GHz portable wireless communications (see Figure 1).

"These results show the great potential of SiGe HBTs for on-chip high-power amplification. The increasing RF performance exhibited by SiGe HBTs has enabled these devices as a new contender for many microwave wireless applications wherein GaAs-based devices had to be used previously," he said. "The ease of Si processing allows SiGe HBTs to be manufactured into very small



emitter feature sizes with relatively low cost. The compatibility between SiGe HBTs and CMOS has made single-chip mixed-signal integration feasible.”

The power SiGe HBTs in question were high-voltage devices, consisting of 160 emitter fingers, with dimensions of $0.9 \times 20.3 \mu\text{m}^2$ for each finger. The total emitter area is about $2900 \mu\text{m}^2$ and is optimised for thermal stability and high PAE.

Before moving on, it is worth noting that R&D is by no means static in the application of III-V alloys in the HBT field. There are likely to be more key announcements over the New Year if recent papers are a guide. For example, C-doped GaAsSb base HBTs without hydrogen passivation are under investigation at NTT Photonics Labs in Japan. Recently, Yasuhiro Oda *et al.*, reported their MOVPE-based work which found that hardly any hydrogen atoms are incorporated into C-doped GaAsSb if the annealing is performed under a hydride atmosphere. Hydrogen concentration in the base was under the detection limit of SIMS measurement. Results like these could mean that the HBT fabrication can be simplified. A relatively high-performance HBT (β_{40} , f_T 300 GHz, f_{max} 200 GHz, and BVCEO 6 V) was made without any dehydrogenation.

Hydrogen is also a factor in other devices notably in HEMTs. A national collaboration in Korea has provided some insight into the performance behaviour of AlGaAs/InGaAs p-HEMTs and how this can be applied to an E/D-mode HEMT. In-Ho Kanga *et al.*, from the Dept. of Information and Communications, Gwangju Institute of Science and Technology (GIST), exposed the gate region of the p-HEMTs to a hydrogen plasma in an RIE chamber, followed by a thermal annealing, prior to gate metallisation.

They found a strong dependence of the threshold voltage, the gate leakage current, and low-frequency noise characteristics on the RF power of the hydrogen plasma and annealing temperature. The selective hydrogen pretreatment (SHP)

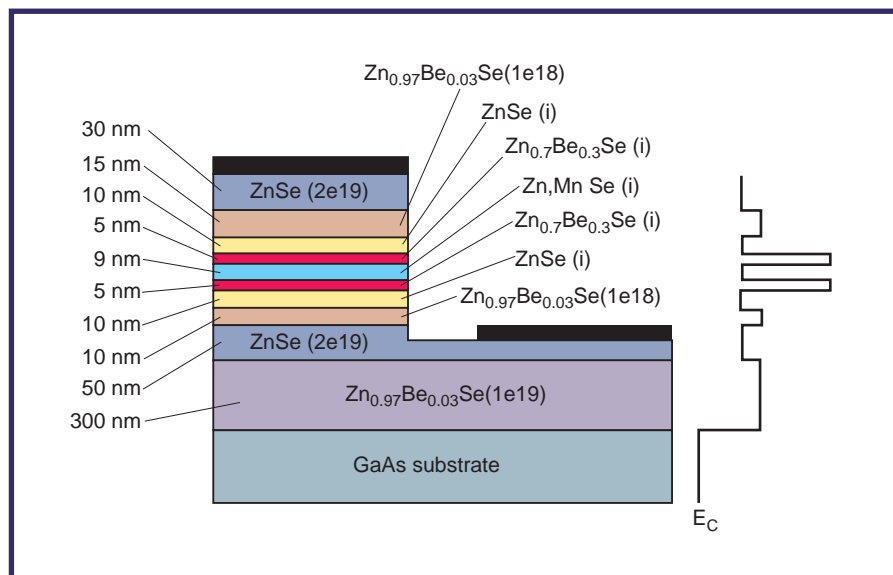


Figure 2: Schematic drawing of the all-II-VI resonant tunnelling diode with (Zn,Be) Se barriers

produced improved gate leakage current, breakdown voltage, and low-frequency characteristics. These results indicate the potential of the selective hydrogen pretreatment for use in an easier fabrication of E/D-HEMTs.

Meanwhile, MA Mastro *et al.* at the US Naval Research Lab, Power Electronic Materials Section, have reported results from their studies of Group III-nitride HBTs. Potentially, these have much to offer for high current handling, high breakdown voltage, and device linearity, etc.

“Despite the many attractive features,” he says, “Progress in III-nitride bipolar electronic devices has lagged the successes enjoyed by AlGaIn/GaN HEMTs. This is due to difficulties associated with growth and processing. There is an alternative which combines the advantages of SiC and GaN systems to yield n-GaN/p-SiC/n-SiC HBTs. This HBT is theoretically capable of higher output power at microwave frequencies and should have a better linear response than SiC BJTs or nitride HBTs. Into the bargain it is much simpler to fabricate than a nitride HBT.”

However, there are problems relating to leakage currents through the n-GaN/p-SiC heterojunction, due to the poor quality of the interface which ultimately limits the output gain. Nevertheless, progress

has been forthcoming - his team have, for the first time, modelled the influence of strain and polarisation fields in (Al)GaN films grown directly on 4H-SiC substrates, yielding band diagrams as well as device I-V parameters. Apparently leakage is made worse by the profusion of dislocations in the (Al)GaN films grown on 4H-SiC without low-temperature GaN or insulating AlN layers. But, as the team showed, onset of misfit dislocation formation can be avoided by nano-heteroepitaxy of (Al)GaN emitters in confined areas or on mesas.

Nanowhiskers

Attention now turns to the more exotic. There has been much discussion in the electronics press as to the potential for nanostructures, as if this was new.

For compound semiconductors this is not the case, since the fabrication of nm-dimension devices has almost become routine. In particular, GaAs quantum wires have been extensively studied because of their potential applications to electronic devices. These quantum effects provide a means of artificially controlling the electrical properties of materials and could lead to the development of new devices. The tools and procedures are in place and numerous interesting developments are underway worldwide. These are likely to be significant for the medium to long term on commercial terms

but from the scientific viewpoint there is much to report. A survey of the literature will yield a surprising amount of interest in a curious form of semiconductor material - that of the needle-shaped 'nanowhiskers'.

Nanowhiskers have diameters of about 10-100nm so they are very effective for investigating electron transport in a narrow channel. In a recent paper from Hitachi's Central Research Laboratory, K Haraguchi, *et al*, have examined the I-V characteristics of GaAs nanowhiskers. Part of the METI R&D Program Quantum Functional Devices Project, MOVPE-grown nanowhiskers with an average diameter of 100nm and a population of 100-1000 have been made and characterised. An ohmic contact to the tip of whiskers which were buried in spin-on glass between a metal electrode and n-type GaAs(111)As substrate. The dependence of the current on the voltage suggests that a space-charge layer was formed in the nanowhiskers. Step-like current fluctuations were also observed at 77K, and this behaviour was reproducible and unchanging even under a magnetic field. This suggests that the charge on the surface of the whiskers had a significant effect on carrier transport along the whiskers. I-V characteristics had to be averaged over a large population of whiskers and so the exact mechanism of current flow in individual whiskers remains unclear. But it was concluded that the surface charge has an important effect on carrier transport in the whiskers.

Other interesting areas of development in nanowhiskers include using different substrates such as silicon. To better understand the conduction mechanisms, Magnus W Larsson of Lund University, Sweden, and his colleagues have used an STM mounted in a TEM sample holder for in-situ electrical measurements of nanowhiskers grown by CBE. It enables measurements and manipulations of nanostructures while observing them in a TEM. In related work, researchers from the Solid-State Physics/Nanometer Consortium at Lund University fabricated a heterostructure

device within a single 40nm-diameter InAs whisker.

MBE is naturally a useful tool for such investigations, thanks to the high quality vacuum. This is the preferred approach for I P Soshnikov and his group at the Ioffe Physicotechnical Institute, St. Petersburg, who have looked into the 'peculiarities of the MBE growth of nanowhiskers on GaAs(100) substrates' in a recent paper. They found that the MBE growth is in two stages (initial and developed) which forms nanowhiskers with surface morphology of two types - nucleation and inter-growth.

Magnetic semiconductors

Dilute magnetic semiconductors (DMS) are a new class of materials with great potential. Basically, magnetic dopants can be used to turn GaAs and other semiconductors into ferromagnetic materials. These combine the advantages of semiconductors with non-volatile properties of magnetic materials. Industry observers see them as the materials foundation for future spintronic technologies.

Spintronics has become one of the rapidly growth fields in electronics. This is due in part to its common use in computer hard drives. It is in computer memories where spintronics has the most potential and current research focuses on bringing magnetic random-access memory (MRAM) to market.

GaAs doped with Mn is the premier dilute magnetic semiconductor (DMS), but there are other compounds with promise for room temperature ferromagnetic devices. Though compatible with GaAs technology, it has drawbacks but MBE is proving a useful tool in overcoming difficulties in DMS III-V materials.

Dietl *et al*, predicted theoretically that ZnO and GaN would exhibit ferromagnetism above room temperature (RT) on doping with Mn. Even though there has been much experimental work on a range of doped DMS no reliable homogeneous material with ferromagnetism above RT has been reported yet.

There is a great interest in spintronics worldwide and Germany is no exception. G Schmidt *et al*, of Physikalisches Institut, University of Würzburg, recently presented the first results demonstrating a giant spin-splitting in an all-II-VI semiconductor resonant tunnelling diode (see Figure 2). These devices are promising for voltage controlled spin filters. The next step will be to show they can be used as spin filters by detecting the spin polarised current at the collector side.

Meanwhile, R Koch *et al* of the Paul-Drude-Institut für Festkörperelektronik, Berlin, are looking at RT operation from MnAs films on GaAs.

They have shown that a single magnetoresistive element, which combines the inherent advantage of a non-volatile output with flexible functionality, can be programmed at run-time to be AND, OR, NAND or NOR. Such MR elements - the storage cells in magnetic RAM - may one day soon become the logic gates of future chameleon processors, whose functionality is provided by the software, they predict.

Electronic skins

Even though some of the foregoing is some way off commercialisation, there are other developments which may look rarified but have great import for III-Vs.

So-called 'macroelectronics' are the main interest for Sigurd Wagner, Professor of Electrical Engineering, and colleagues at Department of Electrical Engineering and PRISM, Princeton University, together with the Division of Engineering and Applied Sciences at Harvard University.

This and other groups are developing 'electronic skins' or 'skin-like' circuits. Basically these comprise an elastomeric skin to support rigid islands, where active subcircuit are made and interconnected by stretchable metallisation.

The islands are made sufficiently rigid to protect them from breaking when the circuit is deformed by stretching, etc. The function may be a liquid crystal, a luminescent or light sensing device, a touch sensor or an actuator element.