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In spite of deep concerns about the spread of severe acute respiratory syndrome in Asia, the 5th International Conference on Nitride Semiconductors at Nara was well attended with 442 presentations (24 countries; 60% from overseas), lively rump sessions and active participation by key figures including Professor Akasaki, the Honorary Chairman of the Conference. Sponsored by the Japan Society of Applied Physics with co-sponsorship by the 162nd Committee on Wide Bandgap Semiconductor Photonic and Electronic Devices of the Japan Society for the Promotion of Science, technical sessions focused on topics ranging from growth and material characterisation to fabrication and commercialisation of devices such as high power FETs and laser diodes. This is a review of talks related to high power devices, AlGaN/GaN FETs, that have recently been the focus of intense scrutiny and may replace GaAs technology in the future.

During the opening plenary session in the breathtaking Noh theatre room, Professor Khan of the University of South Carolina, described developments in the growth, fabrication and performance of III-Nitride heterojunction field effect transistor (HFET) structures and devices. He emphasised that problems associated with surface and bulk traps, rf-current collapse and large gate leakage currents need to be resolved in order to fabricate highly stable HFET devices exhibiting high rf-powers at GHz frequencies.

Solutions to these problems were described as (i) the use of pulsed atomic layer epitaxy for depositing AlN and AlN/AlGaN multilayers with reduced density of dislocations of high Al concentration III-N structures; (ii) reduction of interface states by deposition of high quality insulating silicon dioxide and silicon nitride layers (thickness of less than 10nm) on the surface of AlGaN; (iii) finally, development of new MISD-HFET structures on sapphire substrates employing AlInGaN/InGaN(channel layer)/GaN double heterostructures (which were shown to exhibit less than 0.1nA/mm gate leakage currents, 26GHz rf-powers in excess of 6W/mm and no current collapse. Professor Kahn concluded by describing the potential for commercialisation of device structures grown on 4 inch wafers which showed 3-4% resistance uniformity.

Emcore described the development of its new E300 MOCVD reactors for growth of AlGaN/GaN structures on multiple, 2 inch (21 wafers), 3 inch (8 wafers) and 100mm (5 wafers) substrates. Reactor modelling enables the growth of AlGaN/GaN FET structures exhibiting electron mobilities of 1700 cm²/Vs with a variation of only 4% across a 2-inch wafer. Devices with 0.17μm gate lengths showed current densities up to 1.1A/mm, rf power of 7.6 W/mm at 10GHz, and $f_T$ of 86GHz.

Deep levels and surface states have been found to be responsible for current collapse in HFETs.
A group from Germany’s Research Centre Jülich, described the use of photo ionisation spectroscopy and DLTS to study traps in AlGaN/GaN heterostructures grown on silicon and sapphire substrates. Photo ionisation measurements revealed traps with activation energies of 3.2 eV and 2.9 eV for heterostructures grown on sapphire and at 1.85 eV for HFETs grown on silicon. Backgating current DLTS was used to identify minority (0.54 eV) and majority (0.44 eV) traps near the hetero-interface.

Professor Mishra’s group from UCSB, described the electrical properties and potential applications of polarisation doped 3D electron slabs in graded AlGaN. These unique structures have an electron mobility of about 2700 cm²/Vs at 20K, do not show ionised impurity scattering and the carrier density is independent of temperature; quite different from the carrier transport phenomena observed in doped 3D structures. Low temperature magneto-resistance measurements showed the electron effective mass of the 3D electron slabs to be $m_e = 0.19m_0$. It was stressed that this was the first report on the measurement of the effective mass of 3D carriers, since it is not possible to make such measurements using conventional doped 3D structures because of problems related to carrier freeze out and low electron mobility. Polarised 3D electron slabs will not only be important in studying physics of carrier scattering in semiconductors, but this technology will also be important as a new way of ‘doping’ nitrides without using impurities such as magnesium.

Despite wide spread use of MOCVD for III-N deposition, an alternative was proposed by TDI Inc, USA, with the growth of AlGaN/GaN FETs by HVPE. The advantages of HVPE were given as high growth rates of over 100 µm/hour; carbon free/self cleaning; high quality GaN with record high mobility; cost effective for large area production with 6 inch growth demonstrated and low cost. AlGaN (30nm)/GaN (2µm) FET structures were grown on 2 inch sapphire substrates using Ga, In, Zn and HCl carrier gas. The surfaces were smooth with RMS of 0.3nm over 10x10mm areas. FETs fabricated using these structures ($N_d x 10^{13}$ cm⁻², mobility=800 cm²/Vs) show source-drain currents of 0.6A/mm and transconductance of 100 mS/mm. A new HFET structure, with a 50µm thick AlN buffer layer was proposed; such a structure could only be grown by HVPE due to the very thick layers required.

Having led the world in GaAs FETs development and the ubiquitous HEMT, engineers at Fujitsu now seem to be setting their sights on nitride HEMT structures. The peak electron velocity of GaN has been predicted to be about 2.6 x 10⁷ cm/s but a large electric field of 140kV/cm is required in order to achieve such values. A direct means of applying such large electric fields would be to reduce the gate length. Fujitsu Labs Ltd described the variation of cut-off frequency with gate length for sub-micron T-shaped gate HEMT AlGaN (27nm)/GaN (2µm) hetero-structures grown on (0001) sapphire substrates were used to fabricate HEMT structures with gate lengths between 35nm-800nm by electron beam lithography. Gate widths were 50x2µm and the source drain separation was 2µm with ohmic contacts formed using Ti/Al at 740°C. The room temperature sheet carrier concentration and mobility of the structures were 1x10¹³ cm⁻² and 1200 cm²/Vs, respectively. Best results were achieved for a gate length of 35nm that yielded a cut-off frequency of 102GHz.

Engineers from NEC Corp described the first 'watt level' operation of a 0.25µm short channel single AlGaN/GaN FET chip with an output power of 6.4W/mm at 30GHz. The FET structures were grown on semi-insulating SiC substrates and the use of a ‘field plate’ was shown to be important for improving breakdown voltages and suppressing current collapse. Electrical measurement indicated an average electron transit velocity of 1.7x10⁷ cm²/Vs, almost equal to the theoretical value.

Freiburg-based, Fraunhofer Institute for Applied Solid State Physics, Germany researchers described the use of Aixtron MOVPE reactors (six x 2” wafers) for depositing AlGaN/GaN HEMT structures...
on 2" sapphire and SiC substrates for fabricating 26-40GHz, power amplifiers. At Toshiba R&D Center, engineers have also been studying the use of ‘field plates’ for improving the breakdown voltage of AlGaN/GaN HEMT. The breakdown voltage of a 1.5 micrometre gate length HEMT (gate width of 100x2 micrometers) employing a ‘field plate’ was reported to be as high as 594V, compared with 99V for a structure without the ‘field plate’.

The switching current density of this device was 850A/cm² at a switching voltage of 300V. This is 300 times that of a Si MOSFET.

Among other notables

A group from NTT Basic Research Labs, Japan, reported on the first ever demonstration of a FED using silicon doped AlN field emitters. AlN is promising as a material for field emission because of its nearly zero electron affinity, high physical stability, high thermal conductivity and Si doping, enabling a reduction of the turn on voltages. The FED was described as consisting of a vertical triode structure with Si doped AlN thin films with cold cathode, mesh grid and phosphor coated screen, acting as the anode. The AlN films were 0.4µm thick, had a carrier concentration of 1x10²¹ cm⁻³ and were deposited on n-6H-SiC substrates by MOVPE. Fowler-Nordheim plots confirmed that the currents measured were indeed due to field emission. Typical results showed emission currents of 2µA with an electric field strength of 25V/µm between the AlN surface and grid. The observation that the luminescence area was similar to that of the opening in the grid confirmed that electrons were uniformly emitted from the whole of the AlN surface.

Oki Electric demonstrated an AlGaN/GaN HEMT structure with a record transconductance of 450mS/mm (f_T of 67GHz and f_max of 126 GHz), employing a 0.15µm gate.

The Research Center Jülich group, reported improvements of the DC and RF performance of AlGaN/GaN HEMT by incorporating a carrier supply layer. Aixtron, Germany, described the development of ‘Planetary’ reactors fitted with in-situ reflectometry tools (‘Epi Tune’) for handling 8x4" substrates for growing AlGaN/GaN HEMT structures on 4 inch sapphire substrates.

Furukawa Electric demonstrated the stable operation of AlGaN/GaN HFETs grown on silicon substrates at high temperatures (575K) for up to 100 hours.

APA Optics, USA, described improvements in HFET performance by the use of an AlGaN/GaN 5 period super-lattice (0.1µm thick) as part of a GaN buffer layer in AlGaN/GaN hetero-structures.

The first generation technology consists of industrial goggles with about 112 white LEDs attached around the lenses. The ‘white light goggle headset’ was used during operations. The major problems to resolve were increasing the headset to patient distance (currently a maximum of 52cm when standing); better cooling mechanism (at present the headset use is only tolerable for 15 minutes); and better colour rendition (muscles appear bluish). Web: http://www.yanchers.jp/eng/en_index.html

Trends

Japan and the USA are well ahead in the development of III-N technology with tremendous advances in the performance of high power electron devices, such as the AlGaN/GaN FETs. Although absent due to the SARS scare on this occasion, Taiwan, China and Singapore will play key roles during the mass production of III-N technology.

Major industries in Japan are choosing to outsource the growth of device structures; a strikingly different strategy compared with the development of GaAs/AlGaAs HEMT where the growth, fabrication and sales were all done in-house. Promising new areas to watch in the future will be the III-N integrated and hybrid circuits, high temperature applications, ferromagnetic (Ga,Mn)N for room temperature spintronics and the proliferation of white light LEDs.