COMPOUND SEMICONDUCTOR

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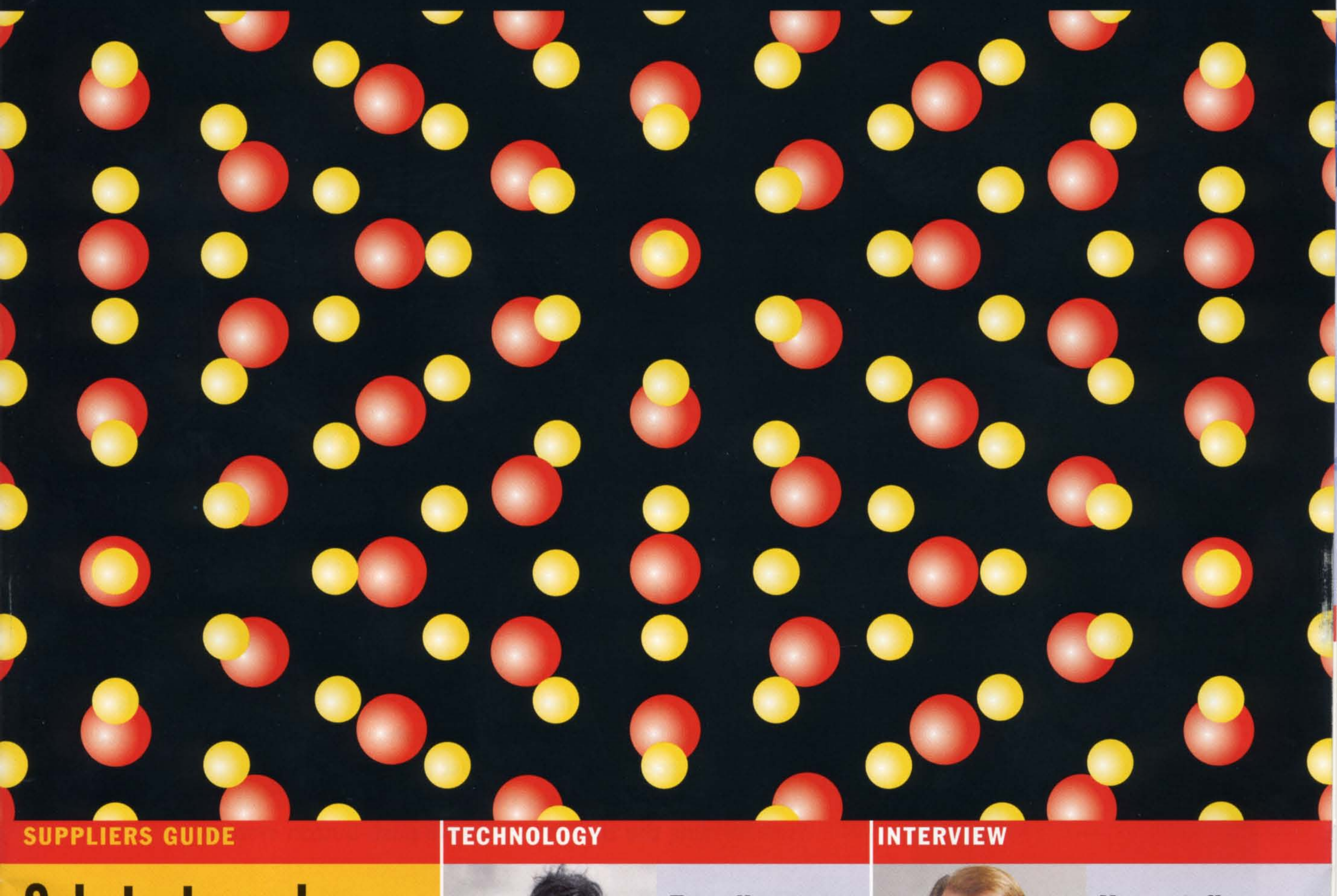
CONNECTING THE COMPOUND SEMICONDUCTOR COMMUNITY

EPITAXY

GaN and germanium: are they perfect partners?



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A life in research: the impact of Klaus Ploog, MBE pioneer

Helmut Jung looks back at the influential career of Klaus Ploog, whose achievements include the invention of the superlattice and the delta-doping technique that are used in today's HEMTs.

Most of us are looking forward to our retirement. It's an opportunity to leave behind the commute, the long hours and the worries about the success of our products, and devote time to the more relaxing things in life.

Academics, however, don't always share this view. Instead, some will continue to work because their research means so much to them. Nobel prize-winning solid-state physicist Sir Neville Mott, for example, carried on writing papers up until his death at 90. Similarly, the German MBE pioneer Klaus Ploog has managed to find a way to continue his research. Although the law of his homeland has forced him retire as director of the Paul-Drude Institute (PDI), Ploog has taken a visiting professorship at Tokyo Institute of Technology, Japan.

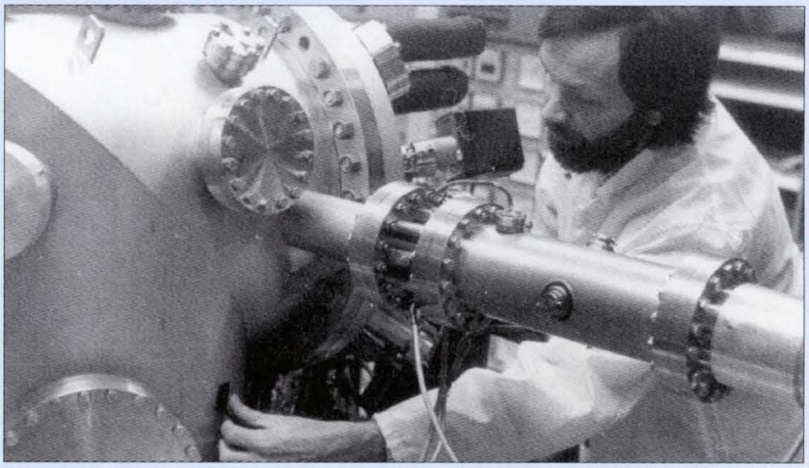
Ploog has been involved in MBE research throughout his career and is a legend within that community. Born in 1941 in Klein Kampen, Germany, he studied chemistry at the universities of Kiel and Munich. After graduating in 1967, he started work as a research scientist at Munich University, and gained a PhD with *summa cum laude* (the highest honour) three years later.

Klaus Ploog's research at Stuttgart and the PDI has left a major impression on academia and industry.

He stayed at Munich as a lecturer for another year, then spent two years as a research associate at the Jülich Research Centre before moving to the Max Planck Institute for Solid-State Research in Stuttgart, where he started to assemble his MBE group. Research in the early 1970s was hampered by a lack of fully equipped commercial MBE tools, and epitaxial effusion cells had to be developed and fabricated in-house. "Often we had to overcome elementary problems," recollects Ploog's colleague Albrecht Fischer. "We had great problems getting boron nitride crucibles for evaporating aluminum."

Despite these difficulties, Ploog built up the expertise required to fabricate high-quality III–V epitaxial structures incorporating dopant atoms. He and his team could then grow semiconductor struc-

Klaus Ploog: a lasting influence



Klaus Ploog's phenomenal career has been felt in industry and academia. He has been granted several patents, including that for the "selectively doped FET" (a structure that we know today as an HEMT), and published more than 1800 technical papers. The importance of these papers is shown by how often they have been referenced. His high number of citations puts him in second place on the all-time *ISI Web of Knowledge* "h-index", with a score of 71 (meaning 71 of his papers have been referenced more than 71 times).

His international awards include:
- 1983 Technology Transfer Award of the Federal Research Ministry, Germany;
- 1989 Award of the Italian Physical Association;
- 1998 Iberdrola Ciencia y Technologia Award, Spain;
- 1990 Philip-Morris Research Award for pioneering work in MBE processes to produce atomically controlled semiconductor layer structures with specific electronic properties;
- 1999 Max Planck Research Award for promotion of internationally outstanding achievements;
- 2003 Welker Award for outstanding contributions on III–V semiconductors;
- 2007 Eugen and Ilse Seibold-DFG award for promotion of the German-Japanese relationship in science.

He has also been a visiting research professor at Stanford University, CA, and the Japanese institutions NTT Basic Research Laboratories, NTT Electrical Communication Laboratories, Mitshubishi Central Research Laboratories, Kyushu Institute of Technology, and Tokyo Institute of Technology.

Ploog fosters international relations

Ploog has held the post of visiting professor at several Japanese institutions, including Waseda University in Tokyo. The high esteem in which he is held in that country, as well as his popularity, is obvious in the way that Yoshiji Horikoshi, a member of Waseda University's board of directors, talks about him: "I first got to know Klaus Ploog in 1982, in Tokyo, during the second International MBE Conference, when he presented an invited speech entitled 'Doping superlattices'.

"After the conference we went to the NTT Basic Research Laboratories in Musashino. At that time he and my boss Dr Okamoto discussed the idea of establishing a researcher exchange program between the two organizations. The program started the following year, and I was honoured to be the first visitor in November 1983. In Stuttgart, all of my family enjoyed the excellent care of Prof. Ploog, his family and all the members of his laboratory.

"Ploog has also established efficient channels of communication and technical exchange between Germany and Asian countries, especially Japan. This relationship is so important to us that I asked him to become a visiting professor at Waseda University, [an offer] which he kindly accepted."

Klaus Ploog (center) enjoys the Vancouver sunshine with former PhD students Yong-Hang Zhang (left) and E Fred Schubert (right), who are now at Arizona State University and Rensselaer Polytechnic Institute in Troy, NY.

Klaus Ploog was director of the Paul Drude Institute from 1992 until his retirement in late 2006.

Klaus Ploog's skills as a researcher were revealed during his time as a PhD student. He was awarded a doctorate *summa cum laude*.

tures with atomic accuracy on GaAs, and then on AlGaAs; work that led to the fabrication of the first tailor-made doped-superlattice structures.

The high-quality samples produced by Ploog's team during this pioneering period were in high demand from academic groups studying quantum mechanical phenomena throughout the world. These researchers included Klaus von Klitzing, who explored his Nobel prize-winning discovery of the quantum Hall effect further with Ploog's material. "Today 'nano' is one of the most important words in modern research," says von Klitzing. "Klaus Ploog contributed enormously to nanoscience and nanoelectronics. When he pioneered the capabilities of MBE for new electronic devices, the word 'nanoscience' was not in use."

Von Klitzing believes that it is only through the epitaxial growth techniques pioneered by Ploog and others, along with the development of scanning-probe techniques, that today's scientists can control materials with atomic precision and subsequently explore the nano-world.

Ploog's influence stretches beyond academia, however. Today's volume manufacturers of transistors are also indebted to his work. The delta-doped layers used in HEMTs, and other devices that confine doping atoms to an ultra-thin layer, were first developed by his group more than 20 years ago. "Delta doping has become the standard doping technique in numerous devices, due to the inherent advantages of delta-doped structures over uniformly doped ones," explains E Fred Schubert, a former PhD student of Ploog's who is now Wellfleet senior constellation professor, Future Chips, at Rensselaer Polytechnic Institute in Troy, NY. "Since its inception, delta doping has been used in billions of devices."

Ploog's other legacy to HEMT production, from around the same period, is the superlattice buffer. This improves the epitaxial quality of the entire tran-

Commercial impact of Ploog's research

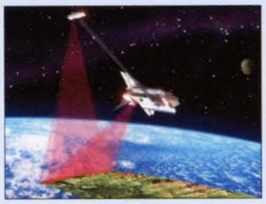
UMS, a European company with manufacturing sites in Ulm, Germany, and Orsay, France, produces a range of amplifiers that feature Klaus Ploog's delta-doping technique and superlattice buffer layer.

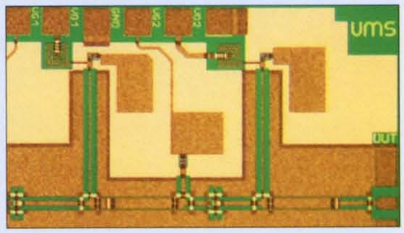
One of the company's PHEMT-based low-noise amplifiers operates at frequencies between 80 and 100 GHz and is used in passive and active radar-imaging systems. This 2 × 1 mm two-stage chip offers low power consumption and is built using the company's proprietary short-gate-length single-recess technology.

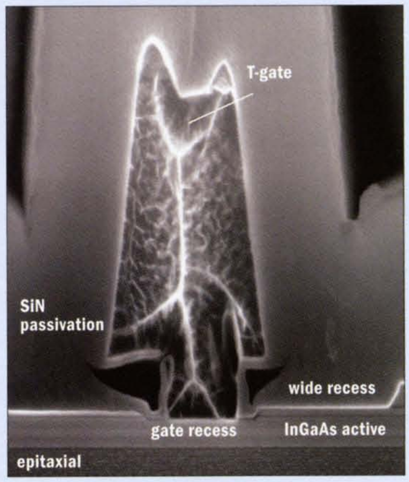
The amplifier's gain, input and output loss characteristics are among the best ever reported for InGaAs/AlGaAs HEMTs, and compare favorably to InP-based and metamorphic technologies.

UMS also makes an amplifier for X-band applications that has a power output comparable to the highest value of its competitors. It features a double recess and double-side doped technology (see figure 1). The PHEMTs used in this device have two etching stop-layers each 1 nm thick, with abrupt interfaces, which provide reproducible recessing.

The amplifier produces an output power of almost 40 dBm (10 W) between 8 GHz and 11 GHz, and a power-added efficiency of 45–50% over that frequency range at 6 dB and 10 dB compression levels.





The PHEMT-based amplifiers produced by UMS are deployed in adaptive cruise-control radar systems in cars, mobile-phone base stations and communication satellites (above). **UMS' PHEMT chip** (top right) targets applications requiring low-noise amplification at 94 GHz. It produces a gain of up to 12.5 dB between 85–98 GHz. Output and input losses at the target frequency are below –20 dB. **Fig. 1 (right).** SEM images reveal UMS' gate structure, featured in its InGaAs/AlGaAs high-power PHEMT structures.

sistor, and is now standard in all HEMT epiwafers.

In 1991 Ploog left Stuttgart to take on the professorship of material science at Darmstadt University, Germany. He didn't stay long, though, and a year later became the director at the newly founded PDI for Solid-State Electronics in east Berlin, at the heart of the freshly reunited Germany. By 1993 he had the additional title of professor of material science at the Humboldt University physics department in Berlin, Germany.

New directions

At the PDI, Ploog continued to push the capabilities of MBE technology, with research that headed in new directions, such as the growth of ferromagnetic semiconductor nanostructures for spintronics and lower-dimensional structures. Developments in all these areas could have major commercial implications in the future. For example, variants of the quantum-wire and quantum-dot structures are now starting to appear in commercial devices such as quantum-dot lasers, while spintronic devices are a hot research topic that could lead to the development of programmable magneto-logic devices.

Ploog has been an active and pioneering developer of wide-bandgap materials based on GaN. When the rest of the community was still focused on polar material, Ploog's team was investigating cubic nitrides and growth on new "non-polar" substrate orientations. His team was also the first to grow GaN by MBE along a non-polar crystal direction.

Non-polar GaN is now a very hot topic. Lasers and LEDs produced using this growth direction promise to have higher efficiencies than their "polar" equivalents, owing to the removal of internal electric fields. There have even been reports this year from UCSB and Rohm of non-polar lasers. HEMTs could also benefit from the non-polar approach, as carriers in the device's channel can be fixed and adjusted by external doping species.

Ploog's research at Stuttgart and the PDI has left a major impression on academia and industry. It has also brought him friends, including many in Japan (see box, "Ploog fosters international relations"), where he has fostered relations between the Japanese and German III–V semiconductor communities. However, his greatest contribution is helping to establish MBE as a *de facto* tool for growing high-quality devices. The techniques that he established are now used to produce various III–V transistors at foundries throughout the world, including the one in Europe owned by United Monolithic Semiconductors (UMS), where the author of this article works.

Further reading

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About the author

Helmut Jung (jung@ums-ulm.de) has worked at UMS since its inception in 1996, and for the first five years he was in charge of PHEMT development and process control. He is now responsible for technology co-operations, and heavily involved in power PHEMT and GaN HEMT development. Before joining the company he worked for DaimlerChrysler, developing InP- and GaAs-based lasers, GaAs-based diodes, PHEMTs and MESFETs. Prior to this he was one of Klaus Ploog's PhD students, investigating laser sub-band transitions in single and multiple quantum wells.
Jung thanks his colleagues J Grünenpütt, H Blanck and Z Ouarch for their contributions to MMIC development.