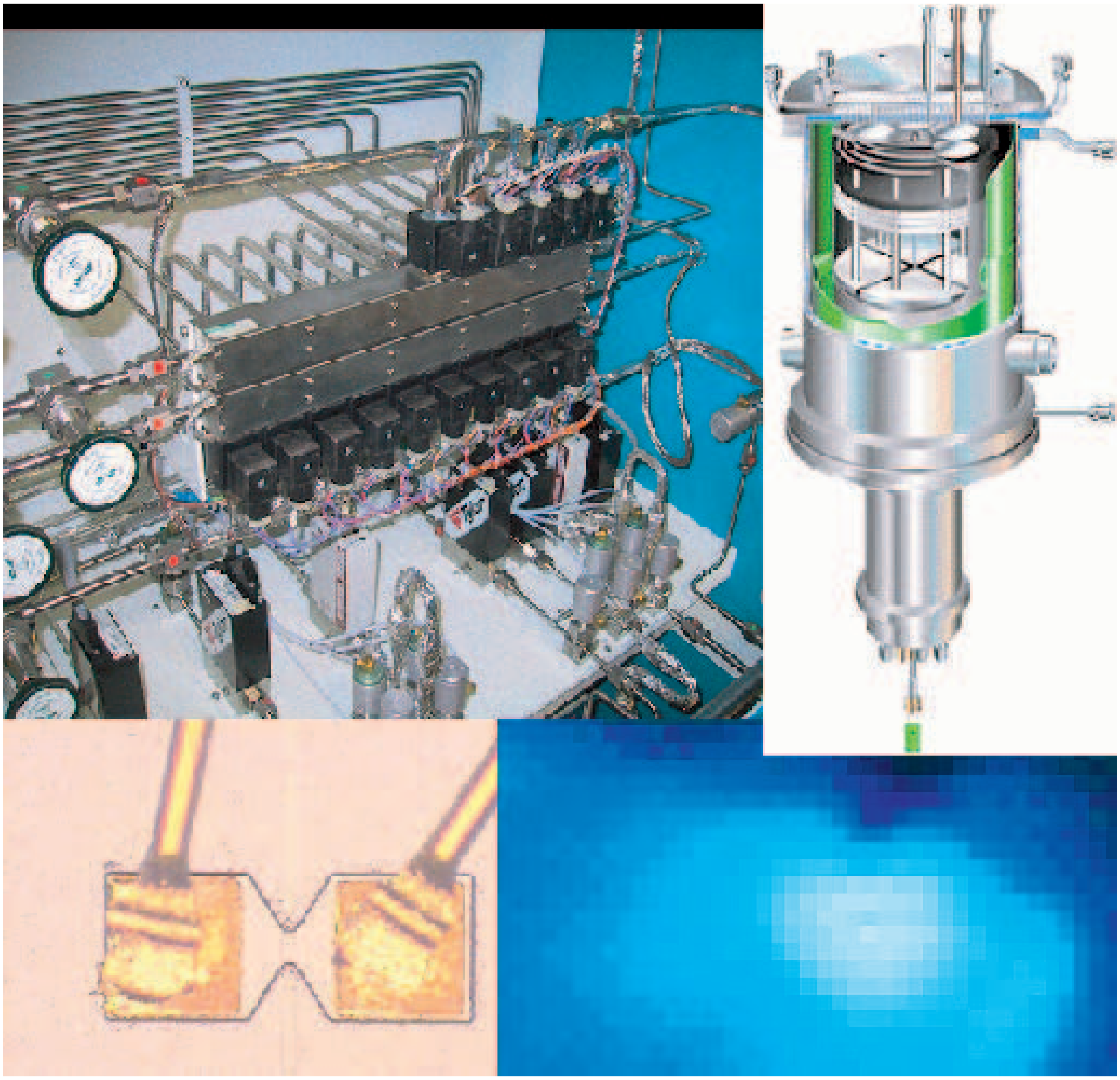

Wide- and Narrow-Bandgap Semiconductor Materials

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Wide- and narrow-bandgap materials are investigated for devices that allow one to attain frequencies that span over a wide range and attain THz. Nanoscale dimensions are employed as obtained by growth or post-processing. Applications span from communications to biomedical engineering

Breit- und engbandige Halbleitermaterialien

Breit- und engbandige Halbleitermaterialien wurden in Hinblick auf Komponenten untersucht, die in einem sehr breitbandingen Frequenzbereich bis THz verwendet werden können. Sowohl beim Wachstum der Materialien, als auch in ihrer Mikro- und Nanostrukturierung werden Nanotechnologien verwendet. Anwendungen für solche Bauelemente findet man im Bereich der Kommunikation und der biomedizinischen Technologie.

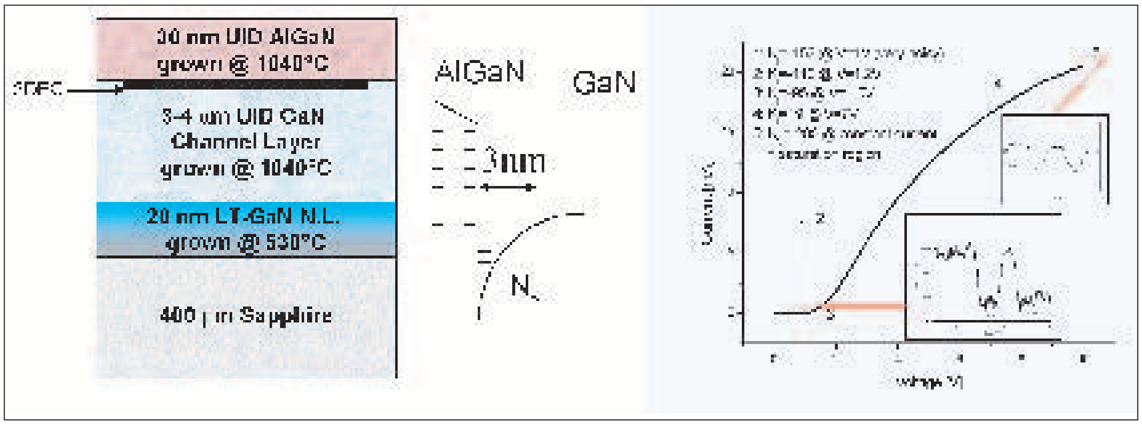

Fig. 1
Layer structure and band-diagram of an electron channel with nanosize dimensions used for pressure sensing.

Schichtstruktur und Band-diagram eines Elektronen-kanals im Nanometerbe-reich für Drucksensoren-anwendung.

Response of high sensitivity sensor for various bias voltages.

Sensorantwort für unter-schiedliche Versorgungs-spannungen mit höchsten Druckempfindlichkeiten.

Semiconductor components have traditionally been based on silicon. Other materials such as III-V compound semiconductors have also attracted the interest of researchers over the last 40 years; but it is over the last 20 years that they made their way to the commercial arena representing a small but valuable part of products. Devices used daily, such as cell phones and satellite receivers take advantage of the unique properties of III-Vs to respond to system needs in the best possible way in terms of high frequency power and low-noise requirements. Sophisticated radars for automotive and other applications are also taking advantage of these semiconductors. A unique feature of non Si-based semiconductors is the plethora of material options that they offer through the possibility of combining two, three or more elements from the periodic table. Examples of these are GaAs, InP, GaN, ZnO, MgO, GaAsSb, InGaAs, AlGaN, InGaN and more. The only exception to this is the SiGe family of semiconductors, which although very promising, does not have the same versatile range of applications that other semiconductors possess. Each of the above materials can be distinguished through a property unique only to them: their bandgap. Narrow- and wide-bandgap materials cover the sub-eV to several eVs spectrum and open the way to a multitude of different applications that range from communications to biomedical engineering. Combined with other materials such as ferroelectrics, they can lead to very sophisticated functions that address tuning and high frequency requirements that span to the sub-millimeter-wave regime. All of the above materials offer exciting controlled properties based on nanostructuring and nanoparticle formation. These can be selected during material growth or by processing. Examples of the attractive possibilities offered by narrow- and wide-bandgap semiconductors are provided and discussed in more detail below.

Widebandgap semiconductors such as nitrides respond to needs where neither Si or traditional III-Vs can provide a solution. Short wavelength light emitters (LEDs and Laser) in the blue and UV region of the spectrum are an example of them. Short wavelength (blue and UV) lasers also have a huge market potential for high-capacity DVD media and high resolution laser printers. The use of a blue wavelength in DVD optical storage devices can increase the storage capacity by almost 6 times (~30 GB DVD capacity for blue laser compared to 5GB for the current red laser technology). Potential applications also include electronic sensors inside the high temperature environments of automobile engines, gas turbines or other harsh environments, high-power amplifiers for cellular base stations to improve coverage area and signal to noise ratio, broadband communication for military application, high-power/high-speed switches, compact power sources, and broadband high-power phased array systems. In addition to their high carrier velocity and high breakdown field opening the way to high frequency, high-power applications, widebandgap semiconductors such as nitrides present spontaneous and piezoelectric polarizations exceeding those of conventional III-V semiconductors by more than an order of magnitude. Spontaneous polarization fields and strain-generated piezoelectric polarization fields present in pseudomorphic AlGaN/GaN or InGaN/GaN structures, may be as high as 3 MV/cm and 2 MV/cm. These very high polarization fields lead in extremely high sheet carrier concentrations in the order of 10^{13} cm^{-2} at the heterointerface.

Wide Band-Gap (WBG) Semiconductors are expected to play a fundamental role in the development of

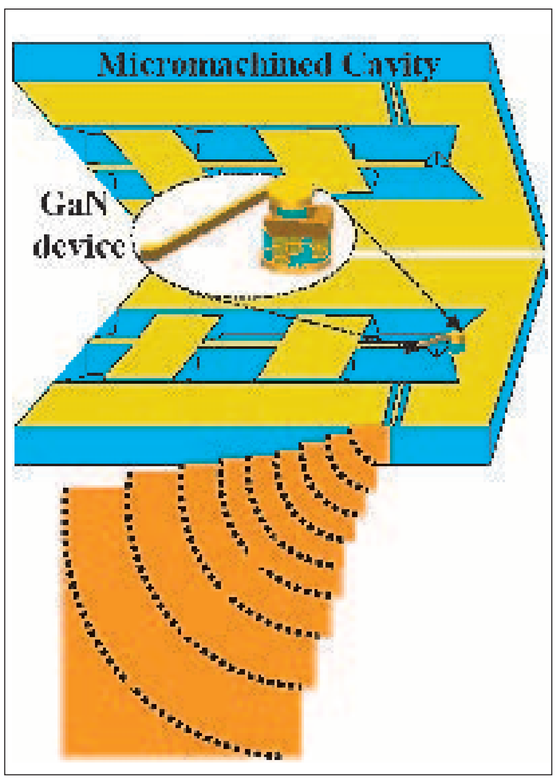

Fig. 2
Schematic view of THz signal generation using an NDR Nitride Device and micromachined circuitry.

Prinzip von THz Signaler-zeugung basierend auf NDR Nitrid-Komponenten und „micromachined“ Schaltungen.

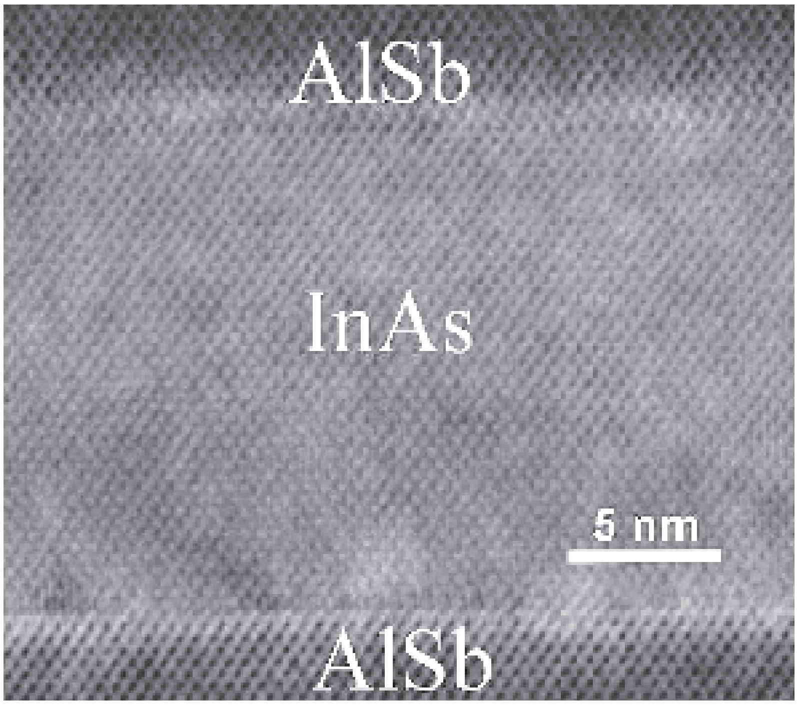

Fig. 3
Atomic resolution of crystalline structures is possible using high resolution electron transmission microscopy. The picture shows a nanometer AlSb/InAs Quantum well that could allow THz signal generation.

Mittels hochauflösender Transmissionselektronenmikroskopie ist eine atomare Auflösung von kristallinen Strukturen möglich. Im Bild ist ein ein Nanometer großer AlSb/InAs-Quantentopf zu sehen, der THz Frequenzen ermöglicht.

Intelligent Microsystems (IMS), yielding unprecedented performance, efficiency and, along with suitable reconfigurable architectures, adaptability to operational changes. Other applications explored by our group include pressure and gas sensors (Fig. 1). Sensors of this type exploit the unique piezoelectric, polarization characteristics, as well as the high temperature stability of wide-bandgap semiconductors in order to allow stable operation with high sensitivity. Using this material system one can also explore the possibility of developing fundamental sources operating in the THz regime and employing Micro-Electro-Mechanical Systems (MEMS) approaches (Fig. 2). Devices of this type operate using the Negative Differential Resistance (NDR) mechanism.

Wurtzitic ZnO is a wide-bandgap semiconductor with a free exciton having a 60-meV binding energy, which permits excitonic emission at room temperature and above paving the way to the brightest ever made emitters. ZnO can also take advantage of already existing native large-area substrates and has excellent resistance to radiation damage. Heterostructures can also be built based on the MgO/ZnO system. These may have potential applications in imaging and electronic control ZnO also has an excellent lattice match to GaN, making ZnO an attractive substrate material. Some of the Co-doped ZnO films exhibit ferromagnetic behaviour with a Curie temperature higher than room temperature.

Of particular importance among the narrow bandgap semiconductors is the GaAsSb material system, which allowed Heterojunction Bipolar Transistors to present terahertz (THz) operation capability. The staggered band lineup at the GaAsSb/InP base-collector junction not only eliminates the electron blocking problem but also allows electrons at the base-collector edge to be ballistically launched into the collector at high initial energies. The velocity overshoot of electrons achieved in the subcollector allows for shorter transport times. Moreover, due to the relatively large energy separation between satellite valleys, electrons launched from base to collector generally do not reach a critical energy for inter-valley transfers. In addition to extremely high frequency devices demonstrated with this system, monolithic integrated circuits such as those demonstrated by our group start proving the ultimate potential capability of these devices.

GaAsSb grown at low-temperature (LT) can also be used as a replacement for the more traditionally recognized material for THz applications. Short carrier lifetimes are necessary for this purpose and THz signals are generated based on photoconductivity. For LT-GaAs hopping between deep level defects (AsGa), which can be found in very high concentrations in non-annealed samples is the main mechanism of conduction. In non-stoichiometric LT-GaAs, metallic As nano-precipitates are formed upon annealing, which reduce the AsGa point defects and lead to high resi-

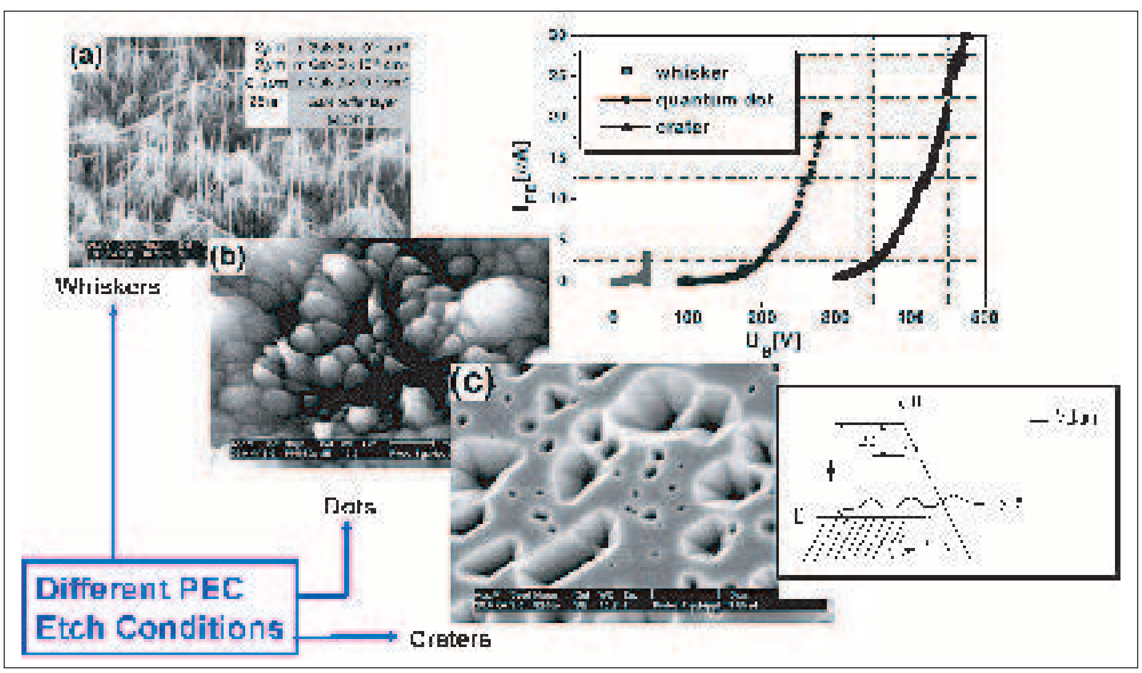

Fig. 4
Field emission from quantum size GaN structures

Feldemission von GaN Strukturen mit Quantenabmessungen.

stance. GaAsSb follows similar trends depending on composition and as demonstrated by our investigations may also be used for THz signal generation offering a major advantage in terms of the type of laser source that is used. By mixing the technology of low- and high-frequency (up to several THz) microelectronics i.e. microwave devices with microfluidic networks one can provide an analytical platform for studying specimens of biological and (bio)chemical origin. This approach allows one to avoid markers that current Polymerase Chain Reaction (PCR) techniques use; markers are needed (1) to detect and quantify DNA; (2) quantify in real time the tested DNA from the sample.

Traditional approaches used so far for THz signal generation were based on femtosecond, as well as solid state lasers and were therefore relatively bulky. Recent progress and new concepts using narrow- and wide-bandgap semiconductors and device concepts such quantum wells with very high mobility (Fig. 3) and plasma waves will lead in THz detectors and emitters. Semiconductors of this type may also be used for other novel applications such as spintronics and field emission (fig. 4). Other approaches include nanometer gates deposited on Quasi-1D channels (Fig. 5).

Spin-based electronic devices employ the spin instead of the charge for information processing. Spintronic devices can be extremely small in size and therefore very attractive for new logic components with lower power consumption and higher degree of functionality than in classical electronic devices. Moreover, spintronics can incorporate novel functionalities by combining for example, magnetic storage of information with electronic readout in the same device. Efficient injection of spin-polarized electrons into nonmagnetic materials, minimization of spin dephasing and the ability of spin control during transport, as well as efficient spin detection are an absolute requirement in these devices and novel concepts using resonant tunneling structures are considered by our group to fully explore their attractive features.

Instead of using very thin emitters for field emission, as for example necessary for vacuum microelectronics one can use semiconductor materials with selected properties. By proper material selection and device geometry one can decrease the work function and introduce quantum size effects that have an impact on field emission. Quantum size GaN whiskers and quantum dots have been studied for this purpose and appear to be very promising for such applications.

Frequency modification of GHz and THz components can be achieved via ferroelectric material in the paraelectric state. Using the electric field dependence and nonlinear behavior of the dielectric constant ε, modification of the resonance frequency, shifting of the phase as well as frequency multiplication can be obtained. Ideal candidates for complex RF components are thin ferroelectric films that can be combined with semiconducting rf devices. $SrTiO_3$ (STO) and $(Ba,Sr)TiO_3$ (BSTO) seems to be most suitable choice of ferroelectric thin films. Studies of this type in integrated form with wide bandgap semiconductors will permit the development of ultra-small chips for sensing and diagnosis and are explored in our group.

The Department of High Frequency Electronics at TU Darmstadt

The Department of High Frequency Electronics has a major research activity in semiconductor growth (MBE, MOCVD), processing and characterization. Narrow i..e Sb-based and Wide-bandgap i.e. nitrides and other III-V compounds are a major part of the activities. Nanostructuring at growth or upon processing is a key to the research. THz signal sources based on NDR and superlattices are also explored Applications cover a wide range of devices, circuits and components for communications, sensors and biomedical engineering.

Contact: www.hf.e-technik.tu-darmstadt.de/en/labs/mwe

The following group members are greatly acknowledged for their contributions to the presentation of this work: Eunjung Cho, Shawn Hsu, Seth Hubbard, Kabula Mutamba, Sanghyun Seo, Jochen Sigmund, William Sutton, Pouya Valizadeh, Oktay Yilmazoglu. Thanks also go to the students, fellows, collegues, as well the agencies and industry that supported the reported work.

Fig. 5
Hochfrequenztransitsor (220 GHz) with 100 nm gatelength and quasi 1D channel.

Hochfrequenztransistor (220 GHz) mit 100 nm Gatelänge und Quasi-1D Kanal.