GaN for THz Sources

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The unique electrical and thermal properties of GaN are used to improve two different approaches to generate THz radiation. One method is heterodyne photomixing, where two laser beams with slightly different wavelengths illuminate an ultrafast photodetector. The electrical and mainly the thermal limits of the conventionally used LT-GaAs restrict the THz output power generated by this method up to now. In a second approach, ultrafast transistors, e.g. hetero field effect transistors, are applied in high power high frequency oscillator circuits that act as input for a frequency multiplier chain. In this approach we investigate the utilization of GaN based transistors. Devices in this material system are usually used for high power applications at moderate frequencies, but the very high electron saturation velocity of GaN allows the application above 100 GHz as well.

1. Introduction

The terahertz frequency band, the region between 300 GHz and 3 THz (Fig. 1), has for a long time been known as the “terra incognita” of the electromagnetic spectrum. On the one side, the frequencies are too high for an electronic approach. On the other side, the photon energy is too low for photonic methods. However, terahertz radiation has tremendous potential for various applications such as radio astronomy, terahertz imaging, high-resolution spectroscopy, medicine, security (“body scanner”) and defence [1-4].

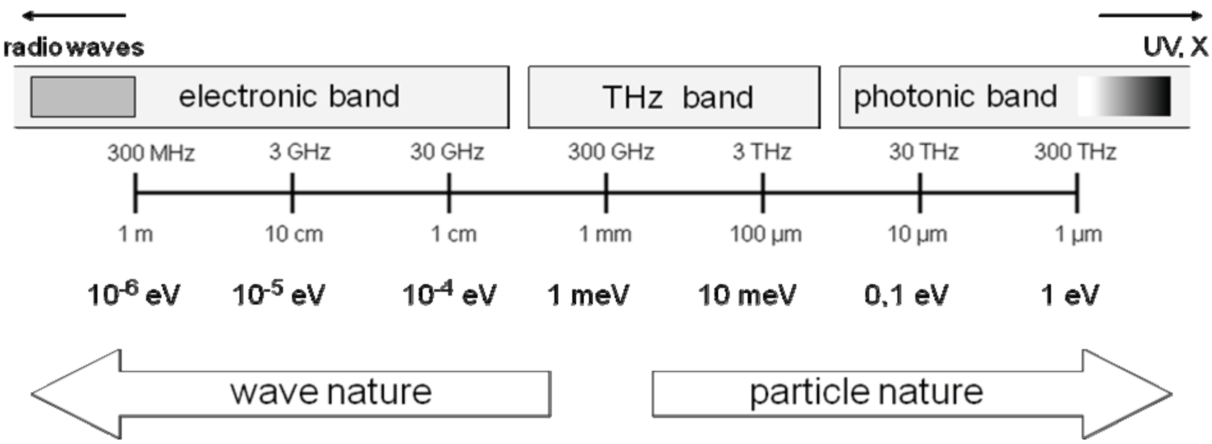

Figure 1: Electromagnetic spectrum, from radio waves to X-rays

During the last years, different methods have been investigated as sources of terahertz radiation. Continuous-wave terahertz sources can be realized by different methods, all with specific strengths and weaknesses (Fig. 2). Backward wave tubes, e.g., are very expensive and

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huge and have large energy consumption, while far infrared lasers need to be cooled down to work at these (for photonic devices) low frequencies.

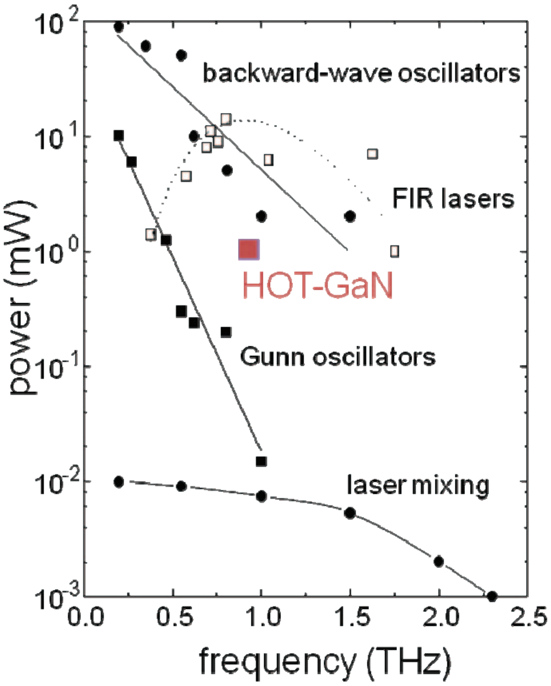

Figure 2: Output power of different continuous-wave THZ sources

Gunn oscillators:
+ reliable and compact technique
- low power for f > 1 THz, expensive

Backward-wave oscillators
+ good tunable
- expensive

F I R lasers
+ high power at > 1 THz
- only discrete frequencies possible
- cooling needed

Laser mixing in LT-GaAs [5-7]
+ up to 3.8 THz, tuneable
- low efficiency

Heterodyne photomixing is a compact and inexpensive approach to generate continuous electromagnetic radiation in the terahertz range, with tuneable frequency [7]. The method uses two lasers with slightly different wavelengths that illuminate an ultrafast photoconductor. The interference of both laser beams creates an oscillation of the illumination intensity in the terahertz range, namely with the difference of both laser frequencies. GaAs grown at low temperatures (LT-GaAs) is the conventionally used photoconductor material [8]. One drawback is the relatively low THz power in the nW to µW range [5-7]. The aim of our work is the improvement of the output power by replacing the LT-GaAs by other semiconductors. For this purpose we investigate GaN that is rather known as basic material for blue LEDs and lasers [9], but it has also remarkable electrical and thermal properties.

A more conventional electronic approach to generate THz radiation consists of the fabrication of an oscillator circuit based on ultrafast transistors, e.g. Hetero Field Effect Transistors (HFET or HEMT) based on InP [10]. These circuits can be designed up to about 100 GHz oscillation frequency [11]. The THz region is achieved by frequency multipliers, e.g. realized by very small-sized Schottky diodes. However, each multiplier stage considerable reduces the output power. In this field we investigate GaN based transistor devices to profit from the much better power performance of this material, compared to classical semiconductors.

2. Photomixing with GaAs:N

The photoconductor is the key element of the heterodyne photomixer. It converts the laser light into an electrical current. Because both laser beams have slightly different wavelengths, the illumination intensity varies with the difference of both laser frequencies. This results in an AC component of the photocurrent that is converted into electromagnetic

radiation by an integrated antenna. Fig. 3 depicts a photomixer chip with finger-shaped photoconductor, dipole antenna and bias lines with integrated RF filter.

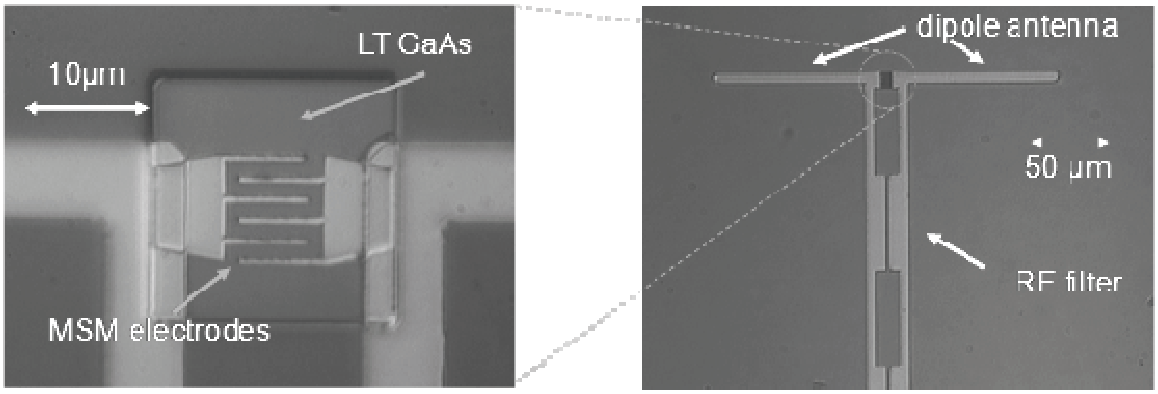

Figure 3: Example of a photomixer chip with dipole antenna, designed for 460 GHz [12]. The photoconductor area is 8x8 μm^2.

The highest frequency that can be generated depends on the speed of the photoconductor. For a well-designed device it is defined by the life time of the photogenerated carriers. The current amplitude and thus the power of the generated electromagnetic radiation depend on the responsivity and the applied bias voltage. The conventionally used material of choice for the photoconductor is GaAs, fabricated by molecular-beam epitaxy at a relatively low temperature of about 200 - 300°C [8]. This LT-GaAs has many defects that act as carrier traps. It shows a subpicosecond photocarrier trapping time (Fig. 4, left) and acceptably high carrier mobility [13, 14]. LT-GaAs photodetectors allow photocurrent pulses in the sub-ps range [15]. The output power of an LT-GaAs photomixer depends on the illumination density and on the applied bias voltage; it is limited by the thermal damage threshold of the material of about 1 mW/μm^2). Best published values are in the μW-range for a frequency of 1 THz [5-7].

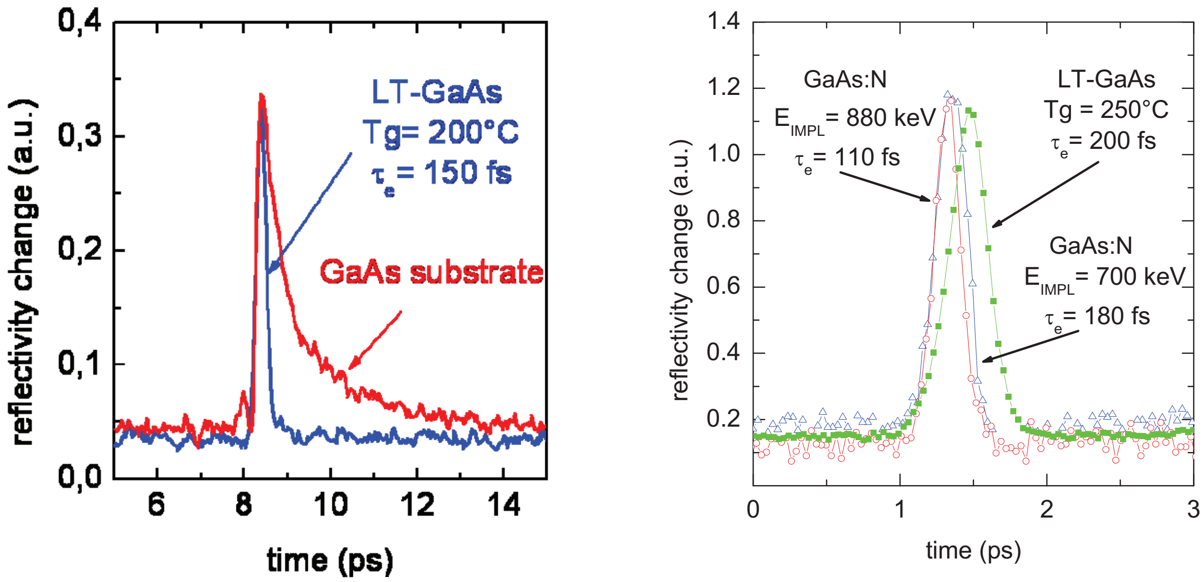

Figure 4: Life time of photogenerated carriers in different material systems, determined by optical reflectivity change measured using femtosecond pump/probe spectroscopy.

τ_e = 1/e - decay time. [16, 17]

One attempt to increase the output power of the photomixer is the exchange of the LT-GaAs by nitrogen-implanted GaAs (GaAs:N). Implantation of nitrogen ions creates carrier defects similar as in LT-GaAs, but with different carrier trap properties. The appropriate choice of doping dose, implantation energy and annealing temperature gives a material with photocarrier trapping times comparable and even lower than for LT-GaAs (Fig. 4, right). Photomixer circuits based on this material show a three-times higher output power than similar devices based on LT-GaAs (Fig, 5) [17, 18]. Also the dependence on the optical input power shows an improved performance, compared to the conventional LT-GaAs based systems. We attribute this superior behavior of the implanted material to the different, as compared to LT-GaAs, physical origin of the implantation defects that act as carrier traps.

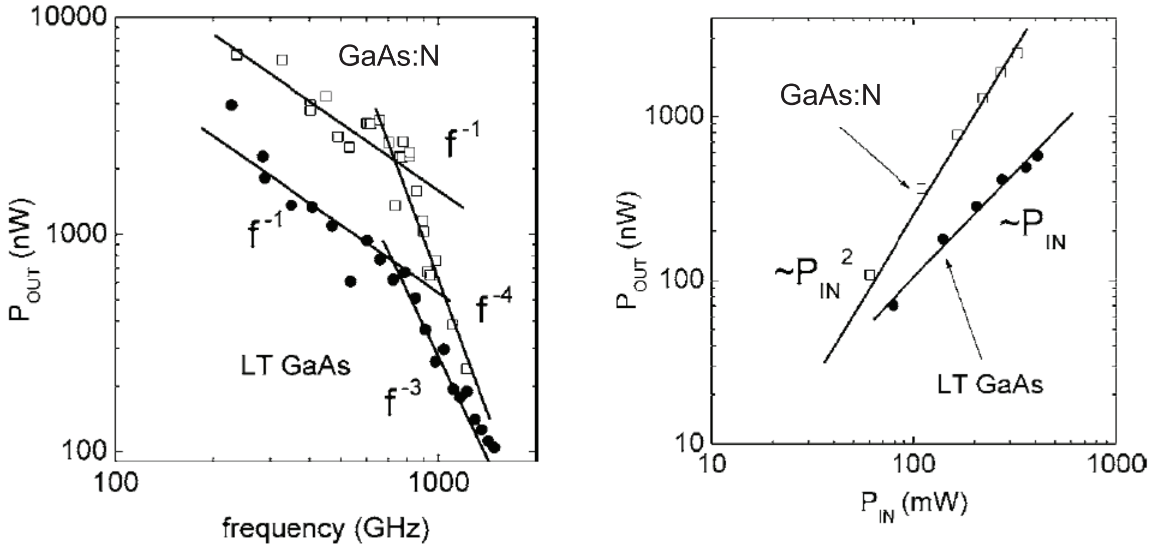

Figure 5: Comparison of the terahertz output power of traveling-wave photomixers fabricated on LT GaAs and on nitrogen implanted GaAs [18].
Left: optical input power: 400mW, bias voltage: 15 V
Right: frequency: 850 GHz, bias voltage: 15 V

3. Terahertz generation by frequency multiplying

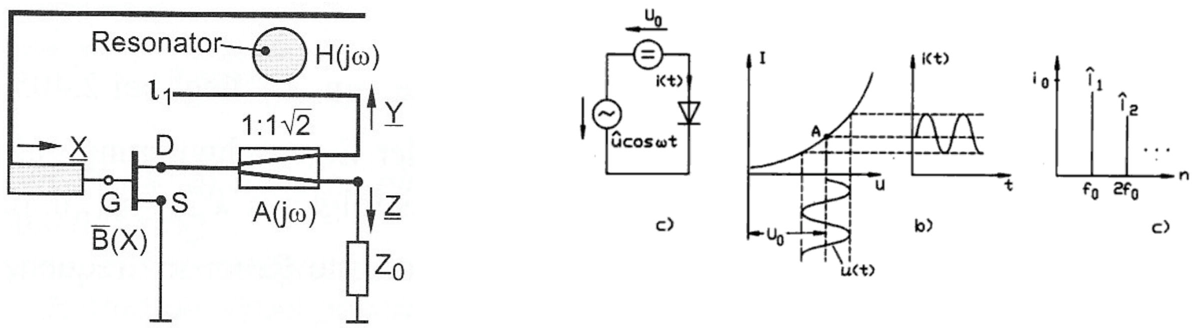

Figure 6: Schematic diagram of the components for the electronic generation of THz radiation.

Circuit of a transistor-based oscillator (left).
Frequency multiplication by a nonlinear device characteristic (right). [19]

Because of the lack of amplifier devices with cutoff frequencies above 1 THz the electronic generation of THz radiation must be performed by the combination of an oscillator with a lower frequency (typically below 100 GHz) and one or several frequency multiplier stages (Fig. 6). The output power of the oscillator must be high to compensate the power loss in the frequency multipliers. Any dipole with nonlinear characteristic can be used as multiplier, e.g. a Schottky diode [20] or a heterostructure quantum well device [21]. A hybrid solution with an external microwave source and cascaded multiplier modules have already been commercialized [22]. The key for a low-cost and compact THz source, however, lies in the monolithic integration of oscillator and frequency multipliers. InP-based devices are up to now commonly used for ultra high frequency applications [10].

3.1 The project "HOT-GaN"

GaN with its very high electron saturation velocity (Fig. 7, left), high breakdown voltage (Fig. 7, right) and elevated operation temperature shows the highest power density and combined frequency-power performance of all commonly used semiconductors (Fig.7, right). While GaN-based transistors are widely used for high power applications at frequencies in the lower GHz range [23], the material system has also shown its potential for high frequency integrated circuits, e.g. as monolithically integrated power amplifier at 76 GHz with an output power of 12 dBm [24].

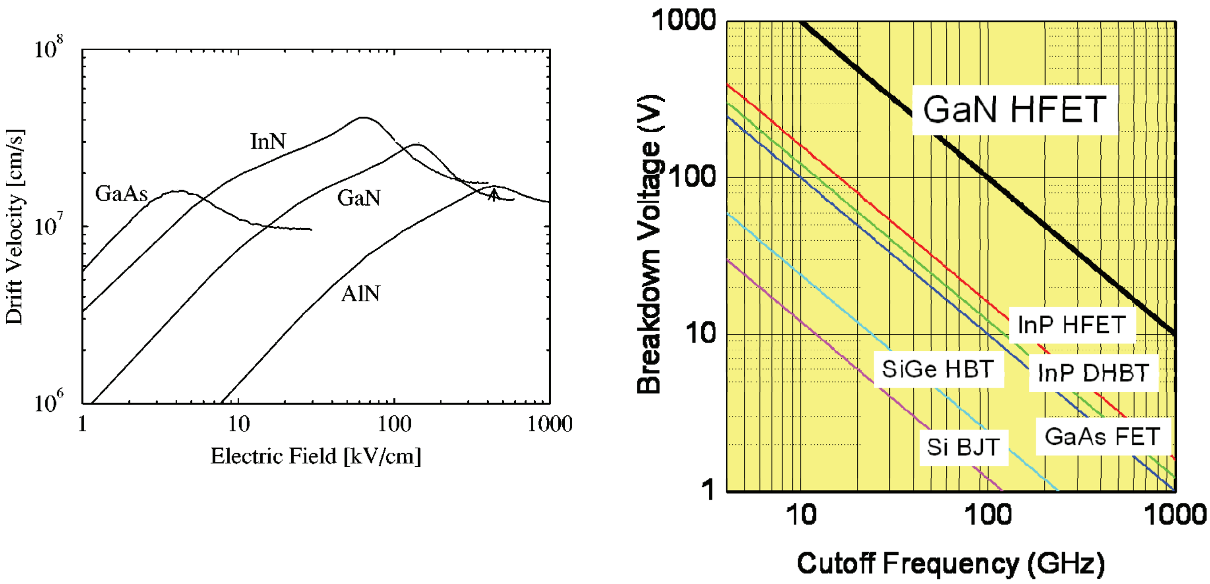

Figure 7: Comparison of electron velocity (left) and device performance (Johnson's limit, right) for different semiconductor materials and devices. [25, 26]

The aim of our project "HOT-GaN" (HFET Oscillator for Terahertz Generation based on GaN) is the development of a monolithically integrated source for THz radiation (Fig. 8). The oscillator needs AlGaN/GaN HFET devices with f_{max}- values above the operation frequency of 100 GHz. In a first step we have developed a device with a gate length of 90 nm that exhibits a cutoff frequency of 100 GHz, without any gate recess or passivation [27] (Fig. 9).

In a second step the f_{max}-value will be increased to the required value (above 150 GHz) by application of a T-gate process and recessed gate. Published values show that this challenging high frequency performance is achievable [28, 29].

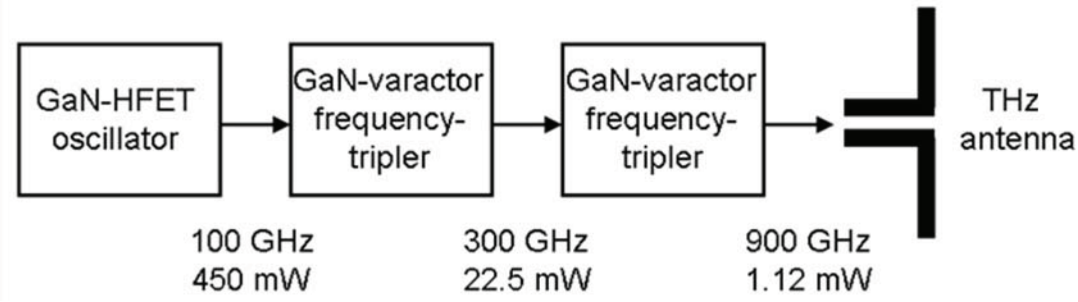

Figure 8: "HOT-GaN" concept: all components are integrated on one chip.

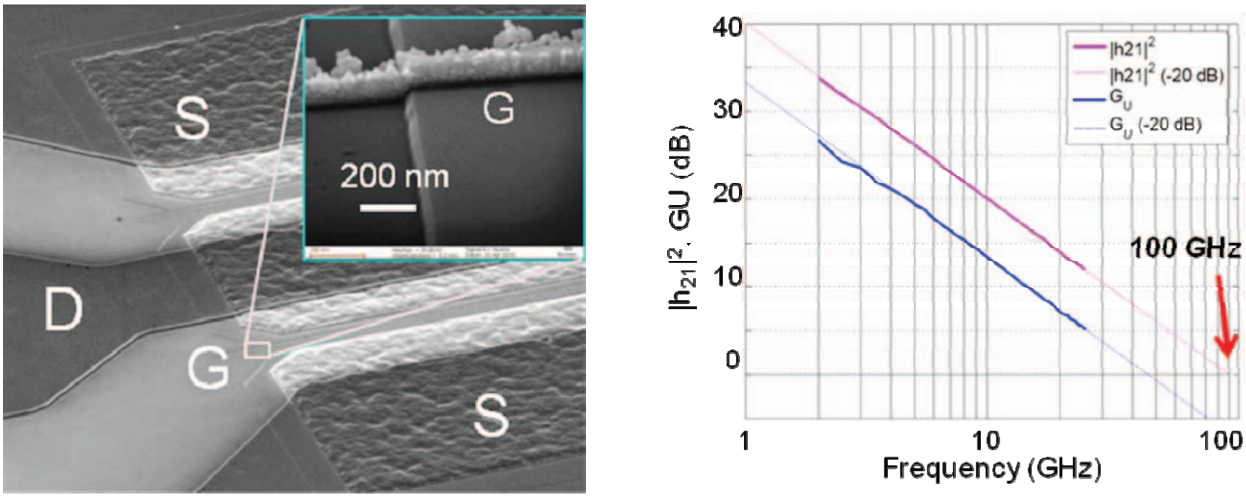

Figure 9: SEM picture and RF performance of an AlGaN/GaN HFET with 90 nm gate length.

The frequency multipliers will be fabricated by GaN MSM diodes. For this purpose we will investigate GaN nanowires that allow the design of diodes with very small areas needed for ultralow capacitances [b5].

The intended performance of the HOT-GaN elements (Fig. 8) will allow the realization of a THz source that is very attractive compared to the existing sources, considering frequency, power, costs and compactness (Fig. 2).

4. LT-GaN for photomixing

Photomixers based on GaN with its high electric breakdown field, high operation temperature and large thermal conductivity could be operated with much higher optical input power and bias voltage than GaAs-based circuits. These excellent properties of GaN will allow sources with much higher THz power, provided that GaN can be grown with ultrafast carrier traps. Up to now, GaN is always grown with a very high defect density (compared to classical semiconductors) because of the lattice mismatch between GaN and substrate. While

these defects reduce the quality of GaN-based transistors, they can be used for fast photodetectors, especially when the material is grown at low temperature (LT-GaN) [31].

The layer structure (100nm AlN /150nm GaN, n = 10^{17} cm^{-3}) was grown by plasma induced molecular beam epitaxy on 6H i-SiC substrate at 650°C. The photodetector with an active area of 15x15 μm^2 was fabricated on the upper LT GaN layer. Interdigitated MSM structures with finger width and spacing of 1 µm and 2 µm, respectively, consist of standard Ni/Au Schottky contacts [32]. The time-dependent performance of the prepared LT GaN MSM photodetector was investigated by a standard pump-probe time resolved experiment using a femtosecond sapphire laser with frequency doubling (360 nm). The pulse energy used in the measurements was 68 pJ per 100 fs pulse. Figure 10 shows the response of the photodetector with a full width at half maximum value of 0.9 ps. The frequency response, calculated by Fourier transform, yields a bandwidth of 410 GHz. Comparison of these results with typical LT-GaAs values (0.58 ps and 550 GHz for FWHM and bandwidth, respectively [15]) prove the suitability of this novel material for a photomixer with both high output frequency and power.

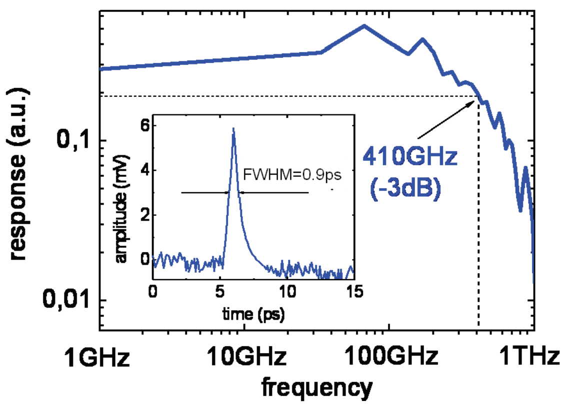

Figure 10:
Time-resolved response of a LT-GaN photodetector (inset) and frequency response (calculated by Fourier transform of the time-resolved response)
(2V bias voltage)

5. Conclusions

We have demonstrated the potential of GaN for the improvement of THz sources. The GaAs:N material system has yielded a threefold output power of heterodyne photomixers, compared to the conventional LT-GaAs. A photodetector based on low-temperature grown GaN has shown a sub-ps photoresponse. In combination with the superior electrical and thermal performance of GaN, this result will allow the realization of photomixing systems in the THz range with a large increase of the output power, compared with the existing material systems.

Because GaN based transistor devices and circuits allow a very high power density AND can operate at very high frequencies, this material system is the ideal candidate for the realization of compact monolithically integrated THz sources based on electronic oscillator circuits with integrated frequency multipliers.

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