ABSTRACT For the first time, Gallium Nitride(GaN)-based Gunn diodes with side-contact and field-plate technologies were fabricated and measured with reliable characteristics. A high negative differential resistance (NDR) region was characterised for the GaN Gunn effect using side-contact technology. The I-V measurement of the THz diode showed the ohmic and the Gunn effect region with high forward current of 0.65 A and high current drop of approximately 100 mA for a small ring diode width $w_d$ of 1.5 $\mu$m with 600 nm effective diode height $h_d$ at a small threshold voltage of 8.5 V. This THz diode worked stable due to good passivation as protection from electro-migration and ionisation between the electrodes as well as a better heat sink to the GaN substrate and large side-contacts. The diodes can provide for this thickness a fundamental frequency in the range of 0.3 - 0.4 THz with reliable characteristics.

INDEX TERMS Gallium nitride, gunn diodes, semiconductor structure, terahertz source, side-contact, field-plate.

I. INTRODUCTION

Based on the successful use of the Gunn effect in Gallium Arsenide (GaAs) to generate high-frequency signals, several materials were already tested for their suitability for the same purpose [1]. The aim was to determine the possibilities and conditions for the so-called “electron transfer effect” based on relevant material properties such as energy band profile, charge carrier velocity and mobility. At the same time, attention was also drawn to the potential of so-called nitride materials for operation at much higher frequencies (up to 1 THz) and powers (up to 10 mW). Reasons for this include the achievable high saturation velocity for electrons (for GaN >2 times higher than in GaAs), much higher electric threshold field strength for the so-called “electron transfer effect” (for GaN >50 times higher than in GaAs) and the large energy band gap for higher breakdown voltage [1], [2]. The latter also enabled the development of short-wave optical diodes and semiconductor lasers, which are used in fields such as communications, lighting technology, multimedia, etc. While signal sources based on GaAs and indium phosphide (InP) components have cut-off frequencies of 100 GHz and 200 GHz (for the fundamental mode), respectively, the calculated maximum frequencies for GaN diodes are higher than 700 GHz [1], [3]. So far, simulation for GaN-Gunn diodes [2], [3], as well as several fabrication methods and initial current-voltage characteristics were performed [2], [4]. All of these results were based on Gunn diodes on sapphire substrates. There are several effects and problems that made the verification of the predicted device properties difficult. Typical problems are the occurrence of the electro-migration effects as well as the high series resistances and self-heating [1], [5]. The small thermal conductivity of sapphire makes the implementation of heat sinks difficult. This leads to high DC losses and reduced reliability. A new simulation scheme has been developed in [6]. The simulation results demonstrated the superiority of GaN as a Gunn diode over those based on materials like GaAs and InP. An output power of 1400 kW/cm² is achieved from the GaN Gunn diode, as compared to 4.9 kW/cm² from a GaAs diode. Another approach is described in [7] showing the modulation of the domain mode in the two-dimensional electron gas...
(2DEG) channel of GaN-based high electron mobility transistor (HEMT)-like Gunn diodes by adjusting the electron concentration of the 2DEG near the cathode side and display an explicit numerical study on the GaN-based planar Gunn diode, and demonstrate that the electric field at the cathode side plays an important role on the formation and modulation of the electron domain Gunn diode. In [8], [9], a detailed study about the GaN-based Gunn diode has been presented using an ensemble Monte-Carlo method. The drift velocity, electron density, and electric field distribution as a function of time in the device are illustrated under direct current (DC) and alternating current (AC) bias condition. W. Z. Lee et al. showed in [9] that the Gunn diode with 550 nm transit length is capable to achieve a 500 GHz signal of 2.61 W with 2.27% efficiency under 22 V DC and 5 V RF condition. In [10], an efficient method to improve the crystal quality of GaN Gunn diode with AlGaN hot electron injecting layer on SiC substrate was reported. Multi-channel Gunn diode, which is realized by containing multiple AlGaN/GaN heterostructures as GaN-based HEMT-like planar Gunn diode improves the output power and the characteristics at a higher frequency, was proposed in [11]. In comparison to the prior works from other groups, the novelty of this work besides the GaN substrate is the side-contact and field-plate technologies for smaller effective diode width and height with better field distribution. Moreover, we show the reliability measurements of the NDR region for different diode width and height. So, in this work, we report on the fabrication and characterisation of GaN-based THz Gunn sources using new technology with stable side-contacts. Three benefits were obtained here: good passivation of the active mesa, good heat sink as well as stable diodes with smaller diode height and higher potential THz frequencies.

II. PRINCIPLE OF THE GUNN DIODE
A Gunn diode uses the electron transfer effect by applying a corresponding threshold electric field to generate electron domains which travel through the diode like waves. This results in the generation and subsequent emission of electromagnetic waves corresponding to the domain travelling time. In addition to the main minimum (central valley, gamma (Γ)-valley) of the conduction band, there is a higher secondary minimum (satellite valley) with lower electron mobility. At room temperature and without an external electric field, only the central valley is occupied by electrons. The semiconductor of a Gunn device must fulfill several conditions. On the one hand, the energy difference between the central valley and the satellite valley must be much larger than the thermal energy of the electrons, so that the electrons do not occupy the state of the secondary minima even with small field strengths. On the other hand, the energy difference must be much smaller than the energy gap between the valence band and the lowest conduction band, otherwise the electrons in the central valley will gain enough energy to generate electron-hole pairs, in this case, an avalanche breakdown occurs. These conditions are fulfilled e.g. for compounds with elements of III-V group, such as GaAs, InP and GaN. Especially, for very high frequencies in the terahertz range, GaAs-based semiconductor devices have a number of disadvantages. These are due to the fact that the saturation velocity of the electrons is low and electron transfer times are too high for these high frequencies. Thus, these semiconductor devices are hardly usable for frequencies above 100 GHz. The energy band of the GaAs- and InP-based semiconductor materials have a smaller energy gap to the satellite valley. Electrons are initially in a first minimum (absolute minimum of the Γ-valley) of the conduction band. When electrons reach the energy which is in the range of the energy difference between the first minimum and the second (relative) minimum (satellite-valley), they can scatter with e.g. optical phonons into the neighbouring conduction band minimum. The threshold electric field strength for the so-called “electron transfer effect” is much higher in GaN for high output powers. The electrons have a high effective mass in the adjacent minimum with smaller mobility. For this reason, the electric current drops significantly, despite rising voltage. This results in a negative differential resistance [12]–[17]. Figure 1 shows a cross-section of a standard Gunn diode with an ohmic contact (cathode) on top of the active GaN layer and the second ohmic contact (anode) on the bottom of a mono-crystalline GaN substrate. With the standard diode based on GaN, the NDR was difficult to characterise [18].

![Figure 1. Cross-section of the Gunn diode with the first ohmic contact layer on top of the active layer and second ohmic contact layer on the bottom of the GaN substrate.](image)

III. RESULTS AND DISCUSSION
For improving the standard GaN Gunn diode according to the NDR stability and the heat conduction, side-contact and field-plate technologies were used (Figure 2). The NDR stability is improved because of the large field-plate on the small side-contacts. Furthermore, the heat conduction to the large contact is better and the problem of temperature overheating is partially solved. To fabricate the vertical diodes, a bottom ohmic contact (Ti/Al/Ti/Au) was evaporated and annealed [Figure 2(a)]. The GaN mesa was etched with argon plasma (Oxford system, 300 W, 6.66 Pa) with an etch rate of 24 nm/min using a Si$_x$N$_y$ passivation layer (1 μm) and photoresist mask [Figure 2(b)]. After additional Si$_x$N$_y$ passivation (800 nm), the side-contacts were opened using sulfur hexafluoride (SF6) plasma (Oxford system, 175 W, 16.66 Pa) with an etch rate of 200 nm/min [Figure 2(c)]. Si$_x$N$_y$ passivation layer was deposited using plasma-enhanced chemical vapor deposition (PECVD).
Finally, the field plate was evaporated (Ti/Au - 20 nm/120 nm) which contacted the diode form the side [Figure 2 (d)]. The GaN active layer has a doping concentration as the diode in Figure 1.

**FIGURE 2.** Fabrication process of a Gunn diode with side contact. (a) First, the bottom contact was evaporated (Ti/Al/Ti/Au). (b) Afterwards, the mesa was etched using an argon-based dry etching process. Si$_x$N$_y$ passivation layer and photoresist were used as an etch mask. (c) An additional Si$_x$N$_y$ passivation was deposited and opened for the side-contact using SF6 dry etching. (d) The field plate was evaporated which contacted the diode form the side.

**FIGURE 3.** Top: SEM image of a single diode before field-palate technology with mesa opening for the side-contact. Si$_x$N$_y$ passivation and the photoresist were used as an etch mask. The whole area around the diode was passivated with Si$_x$N$_y$. The photoresist was removed with acetone before the fabrication of the field-plate and side-contact. Bottom: SEM image of the fabricated Gunn diodes in an array configuration with side-contact. The Gunn diode itself is in the middle of the gold field-plate.

For the current-voltage (I-V) characteristics of the GaN Gunn diodes, an in-house made system (Figure 4) was used to measure the incident and the reflected voltage pulses from the Gunn diode and calculate the current–voltage (I-V) characteristics with a LabVIEW program. The wave impedance $Z_0$ was 50 $\Omega$. A DC power supply (TET – ARGOS; 1000 V) loaded the line charger capacitance [outer line (1)] with a charging resistance. The length of the line charger defined the pulse width. A commercial pulse generator (HP 8114A) triggered the power switch based on a MESFET. Both ends of the line charger [inner line (2)] generated the incident wave at closed switch. One line end was used to measure directly the incident wave with an oscilloscope (Tektronix TDS 794D) and the second line end was connected to Gunn diode.

**FIGURE 4.** Schematic of the I-V measurement setup to characterise the GaN Gunn diodes. The setup contains multiple devices controlled by a computer: A pulse generator (HP 8114A), an oscilloscope (Tektronix TDS 794D) and a DC power supply (TET - ARGOS). The inset on the bottom side shows a photograph of the zoomed sample - device under test (DUT) - under the microscope. The length of the line charger defines the pulse-width.
The reflected wave from the Gunn diode was measured with a delay over the line charger. The I-V characteristics were calculated with:

\[
\Gamma = \frac{V_{\text{ref.}}}{V_{\text{inc.}}}, \quad R_{\text{diode}} = \frac{Z_0}{\sqrt{1 - \Gamma}}, \quad V_{\text{diode}} = V_{\text{inc.}} + V_{\text{ref.}}, \quad I_{\text{diode}} = \frac{V_{\text{diode}}}{R_{\text{diode}}} \tag{1, 2, 3, 4}
\]

where \(V_{\text{ref.}}\) is the reflected voltage from the diode, \(V_{\text{inc.}}\) is the incident voltage to the diode, \(\Gamma\) is the reflection coefficient, \(R_{\text{diode}}\) is the diode resistance, \(V_{\text{diode}}\) is the diode voltage, and \(I_{\text{diode}}\) is the diode current. The system can provide a pulse-width down to 20 ns depending on the length of the coaxial cable, an output voltage up to 1000 V and an output current up to 6 A. A 30-dB attenuator is necessary to protect the oscilloscope from the high peak voltages, whereas the short pulse is necessary to minimise the temperature effects and allows reliable measurements of the diode. A bias oscillation was obtained in the reflected pulse above the threshold field 150 kV/cm. It appears due to the diode capacitance and parasitic inductance in the measurement setup similar to [5] which is evidence for the Gunn effect.

Figure 5 shows the measured linear and the NDR regions with a high forward current of 0.65 A, with a small effective diode width \(w_d\) of 1.5 \(\mu\)m at a relatively small threshold voltage \(V_{\text{th}}\) of 8.5 V. Furthermore, the doping and the thickness of the active layer results in high currents through the active layer of the Gunn diode. The effective diode height \(h_{\text{eff}} = \frac{V_{\text{th}}}{150 \text{ kV/cm}}\) was calculated as 600 nm with potential application for up to 330 GHz (\(f = \frac{v_{\text{sat}}}{h_d}\), were the saturation velocity \(v_{\text{sat}}\) is 2 \(\cdot\) 10^7 cm/s). The current drop was up to 100 mA. This fast current modulation is about two orders higher than for conventional GaAs photomixers [19]. The output power is \(P_{\text{out}} \propto \Delta I^2\). These measurements show high potential for high output power especially with much better current modulation compared to the conventional GaAs photomixer. The pulsed measurement of the device leads to lower device temperature at high diode currents during the operation and stabilised the GaN Gunn diode. Figure 6 shows the measured electrical pulse response. The curve shows the bias oscillation due to the Gunn effect which can be seen better in the zoomed inset in Figure 6. The pulse-width was 70 ns. The left pulse corresponds to the input signal, whereas the right one corresponds to the signal reflected from the GaN Gunn diode.

This new approach (Figure 2) enables the fabrication of diodes having smaller width \(w_d\) and height \(h_d\) with more stable NDR characteristics. The current \(I_{\text{max}}\) is depending on the effective width and the frequency on the height of the diode. Instead of 2.5 \(\mu\)m thick diodes (Figure 1) a smaller effective diode height of about 600 nm was fabricated (Figure 2) applicable for higher THz frequencies up to 330 GHz. The highest electric field strength appears at the closest edge between \(w_d\) (cathode) and the substrate (anode), on the other hand, that is also the path which the electron domains are travelling through, resulting in an effective current flow through the channel (Figure 2). The side channel is effectively the thinnest diode region, where the Gunn effect occurs at lower voltages compared to the other areas. The thicker diode areas have only a parasitic current flow, which is not relevant for the Gunn effect. In addition, by using this technology approach, the top contact passivation acts as a protection layer against electro-migration and ionisation between both electrodes. However, the diodes must be optimised in this regard.

To calculate the effective diode channel width \(w_d\) of the ring diode, equation (5) was used.

\[
I_{\text{max}} = v_{\text{sat}} \cdot n \cdot e \cdot A_{\text{eff}} \tag{5}
\]

First, the maximum current \(I_{\text{max}}\) was taken from the measured I-V curve in Figure 5, which corresponds to 0.65 A. Then, the \(A_{\text{eff}}\) was calculated as 100 \(\mu\)m^2 by applying the doping concentration \(n = 2 \cdot 10^{17} \text{cm}^{-3}\) and the saturation velocity \(v_{\text{sat}}\) of about 2 \(\cdot\) 10^7 cm/s. The last step was the calculation of the \(w_d\) using \(A_{\text{eff}}\) and the mesa diameter \(d_{\text{diameter}}\) of 21 \(\mu\)m. The effective \(w_d\) is about 1.5 \(\mu\)m. The effective diode channel height \(h_d\) with side-contact was calculated using equation (6) as 600 nm.

\[
V_{\text{NDR.th}} = E_{\text{Gunn}} \cdot h_d \tag{6}
\]

The theoretical threshold electric field of the GaN Gunn diode \(E_{\text{Gunn}}\) is 150 kV/cm and the NDR threshold voltage \(V_{\text{NDR.th}}\) was taken from the measured I-V curve in Figure 5, which correspond to 8.5 V. Additionally, the total diode
The device shows unstable characteristics at high voltage with stable characteristics. Furthermore, for a lower current drop of 25 mA, the NDR region with a current drop of 50 mA. Therefore, a moderate $h_d$ for a higher $d$ and $w_d$ were characterised regarding the voltage-current characteristics (Figure 7). The measurements showed different I-V characteristics. The higher the diode height $h_d$ the higher the applied threshold voltage and on the other side the wider the diode width $w_d$ the higher the current. As can also be seen in Figure 7, the higher the current the smaller the NDR region. For a lower $h_{d,1}$ (green curve), the NDR region is much bigger (current drop of about 100 mA) than for a higher $h_{d,3}$ (red curve) with a NDR with a current drop of 25 mA. Therefore, a moderate $h_{d,2}$ (blue curve) was chosen for moderate NDR region with a current drop of 50 mA with stable characteristics. Furthermore, for a lower $h_{d,1}$, the device shows unstable characteristics at high voltage (Figure 7, green curve).

The technology of the vertical GaN Gunn diode with side-contact is more sensitive to misalignment and etching optimisation. With the required argon-based dry etching process, rough edges on the mesa structure can be formed. As a result, increased electrical field strengths occur there. This leads occasionally to electrical discharges between the mesa floor and the cathode. The resulting positive ions bombard the cathode metallisation and cause material migration in the direction of the surface of the active GaN Gunn diode region. These can then cause short circuits in the component. The solution is an optimum passivation layer around and on the top of the diode. On the other hand, the fabrication of a side-contact with SF6 dry etching defines the width and the height of the fabricated effective diodes. This needs better technology than the fabrication of the standard vertical diode. This can be seen by comparing the cross-sections of both vertical diodes (Figures 1 and 2). The fabrication of diodes with the same characteristics is still challenging. The side-contacted GaN Gunn diode is better for the fabrication of smaller effective diode area and height for higher device stability and higher oscillation frequency, respectively. Compared to the device designed for 40 GHz, which is reported in [5], this diode is designed for 400 GHz. Additionally, better stability due to the effective passivation of the diode of 800 nm was achieved. Moreover, due to its higher thermal conductivity (130 W/mK), in contrast to sapphire (40 W/mK), the GaN substrate is itself more suitable for heat dissipation. The large field-plate contact supports the effective heat dissipation. The side-contact and field-plate technologies were used for smaller effective diode width and height with better field distribution. The critical mesa edge was passivated and covered by the field-plate. Furthermore, the design of a circle diode contributed to minimising the field peaks at the edges. Thus, the parasitic electrical field peaks at the edge of the standard diode and the electro-migration effects were minimised.

**IV. CONCLUSION**

New GaN Gunn diodes with a good heat sink to the conductive GaN substrate and side-contact were fabricated. With the side-contact technology, stable voltage supply of smaller GaN Gunn diodes with smaller diode height resulting in higher THz frequency performance was possible. The critical mesa edge was passivated and covered by the field-plate. Furthermore, the design of a circle diode contributed to minimising the field peaks at the edges. The parasitic electrical field peaks at the edge of the standard diode and the electro-migration effects were minimised. Thus, the reliability of the THz diode was increased and stable negative differential resistances were measured. A high negative differential resistance region was shown with the new side-contact technology. The measurement showed ohmic and Gunn effect regions with a high forward current of 0.65 A, a high current drop of about 100 mA, a small threshold voltage of 8.5 V and a small effective diode channel height of about 600 nm. The diodes can provide for this thickness a fundamental frequency in the range of 0.3 - 0.4 THz and allow by using higher harmonics or special excitations even frequencies > 1 THz with an integrated antenna. The initial diode resistance was 13.7 $\Omega$ and can be easily matched to an antenna. Thus, the diodes with side-contact and field-plate offer the possibility of directly generating terahertz radiation of relatively high power (>10 mW) at selected target frequencies (up to 400 GHz), which can be set according to the application.

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(‘Ahid S. Hajo and Oktay Yilmazoglu contributed equally to this work.)

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AHID S. HAKO (Member, IEEE) received the master’s degree in physics from the Institute of Physics, Goethe University Frankfurt, in May 2014. He is currently pursuing the Ph.D. degree with the Institute of Microwave Engineering and Photonics (IMP), Technical University of Darmstadt. After the submission of the Master thesis, he worked as an Early-Stage Researcher (ESR). His experience includes the areas of terahertz and nanotechnology for the manufacture of new semiconductor devices for THz sources and detectors. His current research interests include the field of nanowire-based THz Schottky detectors, GaN-based THz Gunn sources as well as CNT-based THz devices for biomedical applications. As a Ph.D. student, he contributed in two patents and more than 15 publications.

OKTAY YILMAZOGLU received the Dr. Ing. and Habilitation degree from the Institute of Microwave Engineering, Technical University of Darmstadt, in 2004 and 2013, respectively. He worked on several projects where compound semiconductor materials and technologies were used to develop sensors and electronic devices on the basis of GaAs, GaN, and ZnO as well as carbon nanotubes and graphene for applications in mechanical engineering and at high-frequency. He has 20 years of expertise in microelectronics and devices. This includes the design, fabrication, and characterisation of 3-D magnetic field sensors, pressure sensors, gas sensors, acceleration sensors, high-frequency diodes, and nanostructured field emission devices for high frequency generation. His work includes the experimental use of 1-D or 2-D materials, as well as the theoretical evaluation of related quantum size effects. He is currently working in the field of THz photomixers as well as CNT- and graphene-based field-emission devices for sensing, electron source, and microwave applications. These resulted in several patents and numerous publications in internationally highly regarded magazines.

ARMIN DADGAR received the Dr. Ing. in physics from TU-Berlin, in 1999, and the Habilitation degree in physics from Otto-von-Guericke-Universität Magdeburg, in 2005, respectively. Since January 2011, he has been a Professor with the Faculty of Science, Institute of Physics, Otto-von-Guericke-Universität Magdeburg. He worked on several projects with compound semiconductor materials like GaN as well as components as FET and HEMT. He is currently working in the field of LED as well as MOCVD and MOVPE. These resulted in several patents and numerous publications in internationally highly regarded magazines.

FRANKO KÜPPERS (Senior Member, IEEE) received the Ph.D. degree from the Technical University of Kaiserslautern, Kaiserslautern, Germany. He is a Fellow of SPIE and a Senior Member of the IEEE photonics and communications section. He was with Siemens and the Deutsche Telekom’s Research and Technology Center, where he directed the Optical Networks Research Group and the Photonic Systems Department, until 2002. He worked at Siemens and was
with Deutsche Telekom, where he directed the Optical Networks Research Group and the Photonic Systems Department, Research and Technology Center, Darmstadt, Germany, until 2002. In 2003, he joined the College of Optical Sciences (COS), University of Arizona (UA), Tucson, AZ, USA, where he served as a tenured Associate Professor of optical sciences, built and ran the Photonic Telecommunication Systems Research Group. He served as the testbed lead for the national Science Foundation Engineering Research Center for Integrated Access Networks (ERC CIAN) with which he is still associated through his position as an Adjunct Professor at the UA COS. He has authored or coauthored more than 100 scientific articles. In 2011, he joined the Institute for Microwave Engineering and Photonics, Darmstadt University of Technology (TU Darmstadt), Germany, where he also held the Chair of Photonics and Optical Communications, where he served as the Institute Director. Since January 2019, he has been with the Skolkovo Institute of Science and Technology, Moscow, Russia, as a Professor and the Director of the Center for Photonics and Quantum Materials.