IEEE Access
Multidisciplinary : Rapid Review : Open Access Journal

Received March 31, 2020, accepted April 22, 2020, date of publication April 29, 2020, date of current version May 18, 2020.

Digital Object Identifier 10.1109/ACCESS.2020.2991309

Reliable GaN-Based THz Gunn Diodes With Side-Contact and Field-Plate Technologies

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This work was supported by the Pioneer Fund for Innovation under Grant 56300803.

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 μm 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/cm^2 is achieved from the GaN Gunn diode, as compared to 4.9 kW/cm^2 from a GaAs diode. Another approach is described in [7] showing the modulation of the domain mode in the two-dimensional electron gas

The associate editor coordinating the review of this manuscript and approving it for publication was Anisul Haque.

(2DEG) channel of GaN-based high electron mobility transistor (HEMT)-like Gunn diodes by adjustment 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 fulfil 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 fulfiled 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].

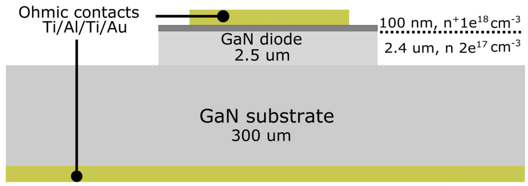

FIGURE 1. Cross-section of the Gunn diode with the first ohmic contact layer on top of the active layer and second ohmic contact layer on the bottom of the GaN substrate.

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_xN_y passivation layer (1 μm) and photoresist mask [Figure 2 (b)]. After additional Si_xN_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_xN_y passivation layer was deposed 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.

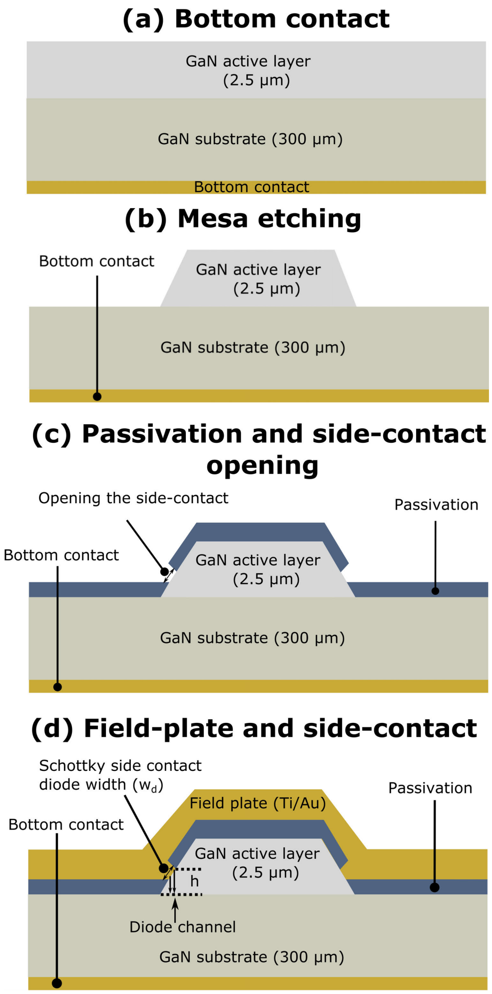

FIGURE 2. **Fabrication process of a Gunn diode with side contact. (a) First, the bottom contact was evaporated (Ti/Al/Ti/Au). (b) Afterwards, the mesa was etched using an argon-based dry etching process. Si_xN_y passivation layer and photoresist were used as an etch mask. (c) An additional Si_xN_y passivation 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 shows the scanning electron microscope (SEM) image of the fabricated Gunn diode. The SEM image of a single diode before field-palate technology with mesa opening for the side-contact can be seen on top of Figure 3. Si_xN_y passivation and the photoresist were used as an etch mask. The whole area around the diode was passivated with Si_xN_y. The photoresist was removed with acetone before the fabrication of the field-plate and side-contact. On the bottom of Figure 3 is a 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. The side-contact is a ring surface.

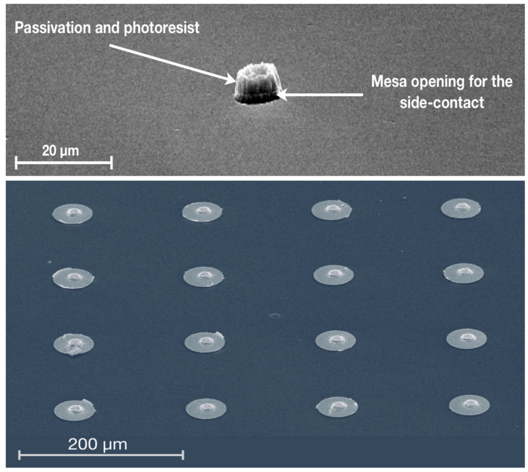

FIGURE 3. **Top: SEM image of a single diode before field-palate technology with mesa opening for the side-contact. Si_xN_y passivation and the photoresist were used as an etch mask. The whole area around the diode was passivated with Si_xN_y. The photoresist was removed with acetone before the fabrication 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 Ω. 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.

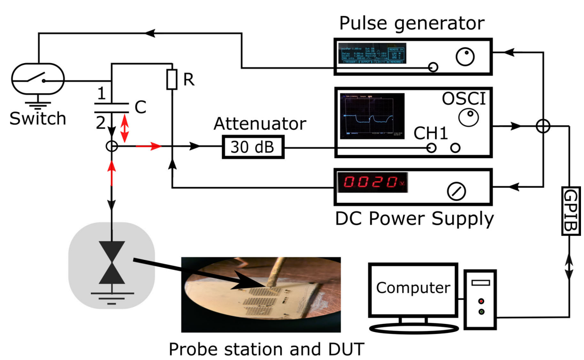

FIGURE 4. **Schematic of the I-V measurement setup to characterise the GaN Gunn diodes. The setup contains multiple devices controlled by a computer: A pulse generator (HP 8114A), an oscilloscope (Tektronix TDS 794D) and a DC power supply (TET - ARGOS). The inset on the bottom side shows a photograph 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:

$$\Gamma = \frac{V_{ref.}}{V_{inc.}} \quad (1)$$

$$R_{diode} = Z_0 \frac{1+\Gamma}{1-\Gamma} \quad (2)$$

$$V_{diode} = V_{inc.} + V_{ref.} \quad (3)$$

$$I_{diode} = \frac{V_{diode}}{R_{diode}} \quad (4)$$

where $V_{ref.}$ is the reflected voltage from the diode, $V_{inc.}$ is the incident voltage to the diode, Γ is the reflection coefficient, R_{diode} is the diode resistance, V_{diode} is the diode voltage, and I_{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 μm at a relatively small threshold voltage V_{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 ($h_d = \frac{V_{th}}{150\,kV/cm}$) was calculated as 600 nm with potential application for up to 330 GHz ($f = \frac{v_{sat}}{h_d}$, were the saturation velocity v_{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 photomixer [19]. The output power is $P_{out} \propto \Delta I^2$. 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_{max} is depending on the effective width and the frequency on the height of the diode. Instead of 2.5 μm 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

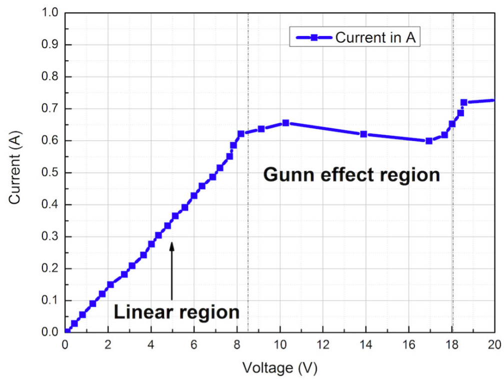

FIGURE 5. Current-voltage curve of the Gunn diode based on GaN with side-contact. The Gunn effect and the ohmic regions are shown.

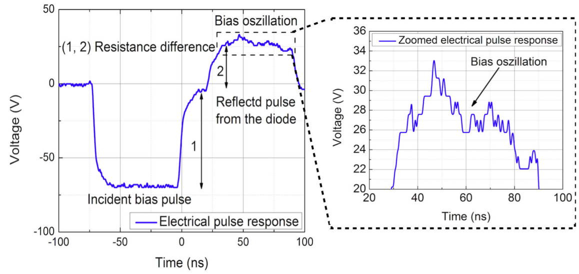

FIGURE 6. Measured electrical pulse response. (Left) shows the incident bias pulse and reflected pulse from the Gunn diode as well as the bias oscillation due to the Gunn effect. (right) Zoomed region of the bias oscillation.

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.

$$I_{max} = v_{sat} \cdot n \cdot e \cdot A_{eff} \quad (5)$$

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

$$V_{NDR,th} = E_{Gunn} \cdot h_d \quad (6)$$

The theoretical threshold electric field of the GaN Gunn diode E_{Gunn} is 150 kV/cm and the NDR threshold voltage $V_{NDR,th}$ was taken from the measured I-V curve in Figure 5, which correspond to 8.5 V. Additionally, the total diode resistance (active layer and contact resistance) was calculated from the linear fit of the ohmic region as 13.7 Ω.

Several diodes with different diode heights h_d and different widths 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).

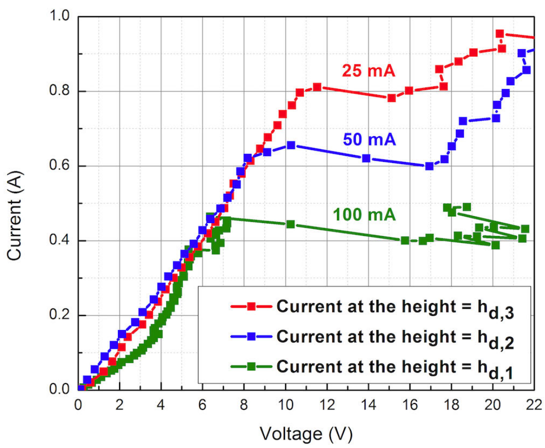

FIGURE 7. **Current-voltage measurements of the Gunn diode with different diode heights h_d.**

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 Ω 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.

ACKNOWLEDGMENT

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

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