Performance Analysis of a two-stage Ga_2O_3 Voltage Multiplier

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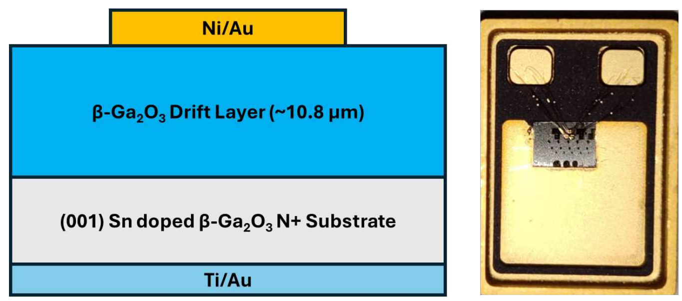
***Abstract*—Ga_2O_3 devices have the potential to replace SiC and GaN devices in high voltage power electronic applications. While development of Ga_2O_3 devices is in its infancy, a clearer picture on its applications will prove to be useful in the future. This paper provides a performance comparison of a commercially available SiC Schottky diode and a Ga_2O_3 Schottky diode, with similar electrical characteristics, fabricated in the authors' university. The diodes are implemented in a two-stage Half-Wave Cockcroft-Walton Voltage Multiplier (VM) application and tested via SPICE simulations. The behavior of both VMs are evaluated and compared in terms of efficiency, output ripple, and voltage gain.**

I. Introduction

Monoclinic Ga_2O_3 possesses properties that make it a very promising candidate for high-voltage power electronic devices. These properties include an ultrawide bandgap of $4.5\,\mathrm{eV}$ and high theoretical breakdown electric field of $>7\,\mathrm{MV\,cm^{-1}}$ [1]. Ga_2O_3 has a Baliga's figure of merit that is several times higher than other wide bandgap materials such as 4H-SiC and GaN. The theoretical device performance (on-state resistance versus breakdown) of Ga_2O_3 also shows an improvement over SiC and GaN. It can be n-type doped with wide range of elements and can be grown from a melt making it a low-cost material [2], [3].

It is imperative to understand the drawbacks of Ga_2O_3 devices in real-world power electronic applications. Low current carrying capability is one such concern at present. Another major challenge in practical Ga_2O_3 devices is its poor thermal conductivity, which is much lower than SiC and GaN [1]. Current packaging and cooling techniques for Si and SiC devices will be insufficient for efficient commercial use of Ga_2O_3 diodes and MOSFETs. While Ga_2O_3 device fabrication is being improved by laboratories around the world, there is a lack of practical applications for gallium oxide devices in literature. A boost converter utilizing a Ga_2O_3 diode was demonstrated in [4]. A Ga_2O_3 diode was used in a buck converter in [5]. Researchers in [6] have shown the experimental performance of a hybrid Cockcroft-Walton Voltage Multiplier (VM) consisting of both Ga_2O_3 and SiC diodes.



(a) (b)

Fig. 1. (a) Cross-section schematic of vertical β-Ga_2O_3 Schottky diode; (b) Picture of the Ga_2O_3 diode package with wire-bonding.

A half-wave Cockcroft-Walton Voltage Multiplier is a suitable candidate to generate an understanding of potential Ga_2O_3 device applications. It is an ac-dc rectifier circuit with high voltage gain capability. It has seen uses in X-ray machines, uninterruptible power supplies and other pulsed current applications [7]–[9]. The high voltage and low current device requirement perfectly satisfy the electrical hindrances mentioned earlier. The low current requirement also reduces the thermal challenges posed when using basic packaging techniques. It is modular in nature allowing for ease in removing and adding Ga_2O_3-based stages after design completion.

In this article, the performance of a Ga_2O_3-based two-stage Half-Wave Cockcroft-Walton Voltage Multiplier was analyzed through SPICE simulations. The behavior of the Ga_2O_3 VM was compared with a commercially available SiC Schottky diode. The SPICE model for the Ga_2O_3 diode was extracted from experimentation on a Ga_2O_3 diode fabricated and packaged in the authors' university.

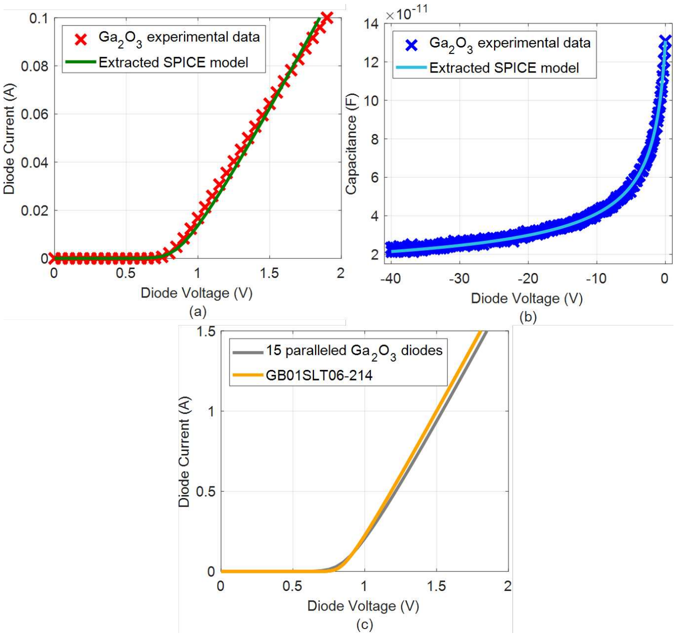


Fig. 2. Forward I-V characteristics of (a) Ga_2O_3 diode through experimental characterization and SPICE model; (b) SPICE model of SiC diode GB01SLT06 and 15 parallel Ga_2O_3 diodes.

II. Device fabrication and SPICE model

The β-Ga_2O_3 Schottky barrier diode was fabricated on commercially available HVPE grown (001) n-Ga_2O_3 with $\sim$10.8 µm thickness (Si-doped, $\sim 2.1 \times 10^{16}\,\text{cm}^{-3}$) on a $\sim$625 µm thick Sn-doped ($\sim 5.4 \times 10^{18}\,\text{cm}^{-3}$) substrate. The device fabrication commenced with BCl_3-based reactive-ion etching (RIE) of the backside; a total of 1 µm thick Ga_2O_3 was etched in this step. Cathode electrodes were formed with a metal stack of Ti/Au (80/120 nm) on the backside of the sample, and Ni/Au (50/150 nm) metal deposition was used to serve as the Schottky contact. The schematic diagram of the device is shown in Fig. 1(a).

The Ga_2O_3 die was was attached onto a SMD10003 package from Spectrum Semiconductor using solder as die attach material. The anode of the diode was bonded onto the package using 25 µm gold wires. The package is shown in Fig. 1(b). After device fabrication and packaging, current-voltage (I-V) measurements were performed using the HP 4155B semiconductor parameter analyzer. A room temperature reverse breakdown measurement was also performed. A standard reverse-biased capacitance-voltage (C-V) measurement was also performed on the Schottky contacts using an Agilent 4294A precision impedance analyzer. The diode was rated at 410 V and 0.1 A.

The I-V and C-V measurement data were used to extract information to generate a SPICE model for the diode. A non-linear regression analysis was performed on the experimental data to fit the following I-V curve [4],

$$I_D = I_S \left\{ \exp\left(\frac{V_D}{NV_t}\right) - 1 \right\} \tag{1}$$

TABLE I

Ga_2O_3 DIODE SPICE PARAMETERS EXTRACTED FROM EXPERIMENTAL DATA

Parameter	Value
Ohmic resistance, R_s	8.67 Ω
Emission coefficient, N	2
Saturation current, I_s	0.3 nA
Zero-bias junction capacitance, C_{jo}	130.9 pF
Grading coefficient, M	2
Junction potential, V_j	1.1 V

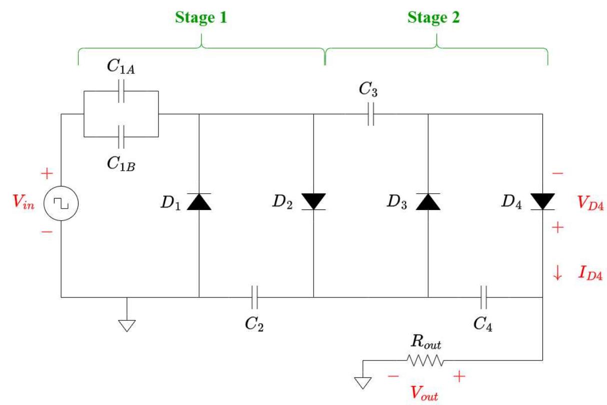


Fig. 3. Circuit Diagram of a two-stage Half Wave Walton-Cockcroft Voltage Multiplier.

TABLE II

CIRCUIT PARAMETERS FOR THE HALF-WAVE COCKCROFT-WALTON VOLTAGE MULTIPLIER

Parameter	Value
Input Voltage, V_{in}	200 V peak-to-peak
Input Frequency, f_{sw}	10 kHz
Capacitance, $0.5C_1 = C_2 = C_3 = C_4$	1 µF
Load resistance, R_{out}	100 kΩ

and the following C-V curve,

$$C = \frac{C_{j0}}{(1 - \frac{V}{V_j})^M} \tag{2}$$

where I_D is the diode current, I_S is the reverse saturation current, V_D is the internal diode voltage (voltage excluding the internal series resistance R_S), N is the ideality factor, V_t is the thermal voltage, C is the reverse-biased capacitance, C_{j0} is the junction capacitance at zero bias voltage, V_j is the contact potential, and M is the junction capacitance grading coefficient. The extracted values are presented in Table I.

The forward I-V and C-V characteristics obtained through device characterization and the extracted SPICE model are shown in Fig. 2(a) and Fig. 2(b) respectively.

III. SPICE simulation

Half-wave Cockcroft-Walton Voltage Multiplier is a rectifier based electric circuit whose aim is to provide a constant dc voltage to the load. It is modular in nature. The circuit diagram for a two-stage half-Wave Cockcroft-Walton Voltage

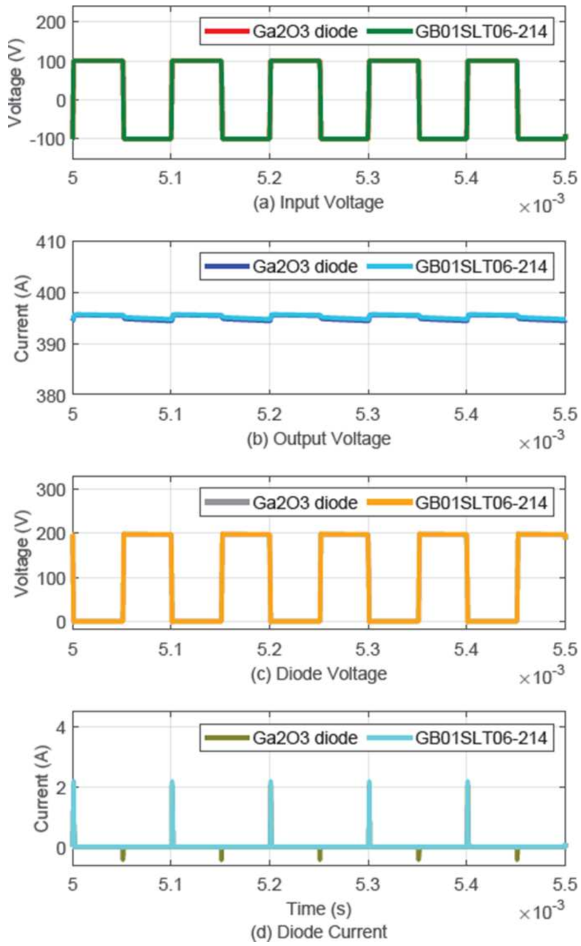


Fig. 4. SPICE results showing of the Ga_2O_3 and SiC Voltage Multiplier showing (a) Input Voltage; (b) Input Current; (c) Diode Voltage; (d) Diode Current.

Multiplier is presented in Fig. 3. Each stage consists of two diodes and two capacitors. One set of diode and capacitor operates each half-cycle of the input voltage to charge the corresponding capacitor. The capacitances of all capacitors in each stage are equal except for Stage 1 where C_1 has twice the capacitance value than other capacitors for optimal design [8]. The design parameters for the Voltage Multiplier are presented in Table II.

An electrically similar SiC Schottky diode was selected to evaluate the behavior of the Ga_2O_3 VM. While the knee voltage for both diodes was similar, the current capacity of the Ga_2O_3 diode was too low for a one-to-one comparison. Therefore, the current of the Ga_2O_3 diode was scaled up by paralleling 15 diodes for a more realistic comparison. In this article, GeneSic's GB01SLT06-214 was chosen [10]. The SPICE forward I-V characteristics of the SiC diode and the 15 paralleled diodes are shown in Fig. 2(b).

The Voltage Multiplier shown in Fig. 3 was simulated in LTspice. The input to the Voltage Multiplier was a $200\,\mathrm{V}$ peak-to-peak square-wave provided by a square-wave generator. This is shown in Fig. 4(a). The no-load output of a two-stage

TABLE III
PERFORMANCE COMPARISON OF SIC AND Ga_2O_3 VOLTAGE MULTIPLIERS.

	Voltage gain, X	Output voltage ripple, V_{ripple} (%)	Efficiency, η (%)
GB01SLT06-214	3.95	0.24	98.13
15 paralleled Ga_2O_3 diodes	3.95	0.24	82.84

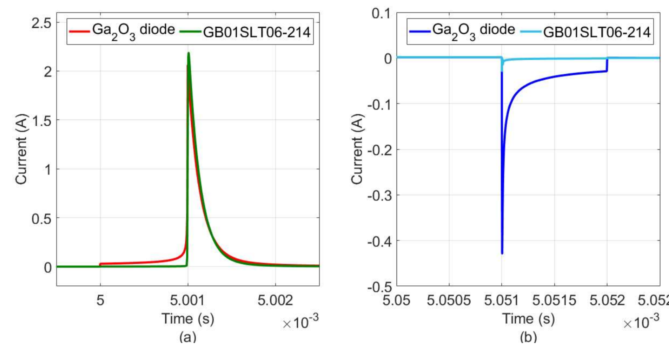


Fig. 5. SPICE results showing diode current in the Voltage Multiplier during (a) Turn-on transient; (b) Turn-off transient.

voltage multiplier is a dc voltage four times the peak of the input voltage. In this case, the output voltage is nearly $400\,\mathrm{V}$ as presented in Fig. 4(b). The voltage drop across the load is attributed to the conduction losses in the diodes. The voltage and current across a single diode are shown in Fig. 4(c) and (d). The switching frequency of the system was kept at $10\,\mathrm{kHz}$ to avoid high current stress on the Ga_2O_3 diode.

The following parameters were calculated from simulations during steady-state to evaluate the performance of the Ga_2O_3 VM,

$$X = \frac{V_{out,avg}}{V_{in,pk}} \tag{3}$$

$$V_{ripple} = \frac{V_{out,max} - V_{out,min}}{V_{out,avg}} \tag{4}$$

$$\eta = \frac{P_{out,avg}}{P_{in,avg}} \tag{5}$$

where X is the voltage gain, $V_{out,avg}$ is the average output voltage, $V_{in,pk}$, $V_{out,max}$ are the peaks of input and output voltage respectively, $V_{rippple}$ is the output voltage ripple, $V_{out,min}$ is the minimum value of output voltage, η is the efficiency of the system, $P_{out,avg}$, $P_{in,avg}$ are average power consumed in the output load and input source respectively. $P_{in,avg}$ was calculated by adding turn-on, turn-off, and conduction losses of all diodes to $P_{out,avg}$. These values are presented in Table III.

The voltage gain and output voltage ripple in both Voltage Multipliers are nearly the same. However, the efficiency has significant drop in the Ga_2O_3 VM. The drop in efficiency is due to the larger junction capacitance of the Ga_2O_3 diode. From the datasheet of the SiC diode, the junction capacitance at zero bias is 50 pF. This is approximately 2.6 times smaller than the Ga_2O_3 diode as shown in Table I. A smaller capacitance for the same voltage transient implies that the SiC diodes have fewer charges that need to recombine during turn-off. This, in turn, reduces the reverse recovery current and losses in the diode. These diode currents during turn-on and turn-off transient in the VM can be observed in Fig. 5.

The similarity in the voltage gain and output ripple shows that a Ga_2O_3 has the potential to replace SiC in power electronic applications. Ga_2O_3 device development is still in its infancy. Improvement to the device structure, especially to the junction capacitance and current carrying capability, could see a further improvement in the behavior of the VM.

IV. Conclusion

In this article, SPICE simulations were conducted on Ga_2O_3 and SiC Voltage Multipliers to evaluate the expected performance of Ga_2O_3 diodes. The SPICE model for the Ga_2O_3 was extracted from a Ga_2O_3 Schottky diode fabricated and packaged in the authors' university. Both VMs were compared on metrics such as efficiency, voltage multiplication factor, and voltage ripple. The Ga_2O_3 and SiC VMs showed similar performance when comparing voltage gain and ripple. However, Ga_2O_3 VM was less efficient than its counterpart due to higher reverse recovery losses. An improvement in device fabrication with focus on junction capacitance reduction and increased current capacity could resolve this issue.

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