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Secondary Ion Mass Spectrometry as a tool to analyze Semiconductor Opening Switch diodes

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The paper presents a Secondary Ion Mass Spectrometry (SIMS) method for the analysis of Semiconductor Opening Switch (SOS) diodes, which are crucial in nanosecond pulsed power systems. The study addresses the gap in experimental measurements of doping concentration in SOS diodes, as the current literature contains mainly theoretical doping profiles. The development of a reliable method for measuring doping concentration is expected to advance SOS technology, given the limited number of manufacturers. The SIMS technique is used to determine the depth distribution and concentration of dopants. The method is adapted to study boron, aluminum, and phosphorus in silicon, with emphasis on detection over several hundred micrometers to clarify the doping profile of SOS diodes. The experimental procedure includes: (i) preparation of the SOS diode sample by cutting, polishing and gold plating, (ii) performing dynamic SIMS analysis using specific conditions for boron/aluminum (O_2^+/M^+) and phosphorus (Cs^+/M^-) detection; (iii) using a line scan mode to measure element intensities across the sample, with quantification based on reference samples. The SIMS conditions developed allowed the depth distribution of the dopants to be measured over a range of 1150 μm with a 2 μm step and providing

sufficient lateral resolution. The quantified profiles of boron, aluminum and phosphorus in the SOS diode are presented. The experimental impurity profiles were in partial agreement with the theoretical doping profiles. This method provides access to the analysis of semiconductor devices with thick structures, which are commonly used in power electronics and solid-state pulsed power.

I. INTRODUCTION

Nanosecond pulsed power systems are used in basic research facilities ^{1,2} and become a major player in novel industrial applications ³⁻⁶. In addition to electrical specifications, characteristics such as pulse repetition frequency (PRF) and long lifetime are required. Discovery of the Semiconductor Opening Switch (SOS) effect led to development of an SOS diode ⁷, which can address nowadays challenges of solid-state pulsed power. The SOS effect refers to the nanosecond interruption of high-density currents in silicon devices, which defines unique properties of SOS diodes to interrupt 10s of kA within 10s of ns and withstand MV-level voltages ⁸.

The switching mechanism of the SOS diodes is well studied and explained according to modern theory ⁹⁻¹³. However, in literature we found only theoretical doping profiles of boron, aluminum and phosphorus. It seems that experimental measurements of doping concentration have not been published in the open literature. As new information of the structure could bring additional knowledge, it would be interesting to verify doping profiles of the SOS diode developing modern structural analysis technique. In addition, SOS diode production is not widespread, with only a few manufacturers worldwide,

which limits its availability. We believe that a reliable method of measuring doping concentration would advance the development of SOS technology.

In the semiconductor field, secondary ion mass spectrometry (SIMS) is usually performed to determine the depth distribution and concentration of dopants. For SIMS analysis, the material is placed under ultra-high vacuum (up to a few 10^{-10} mbar) and sputtered with a beam of primary ions. The secondary ions resulting from the sputtering are collected and sorted by a mass spectrometer. In order to achieve optimum sensitivity, elements with a low potential for first ionization (as boron and aluminum) are detected as positive secondary ions whereas elements with an electro-negative feature (as phosphorus) are detected as negative secondary ions.

In this work, we propose to investigate SOS diodes by applying and adjusting our SIMS method of studying boron, aluminum and phosphorus in silicon. Even if SIMS analysis is generally used for depth profiling in the range of a few micrometers into the material volumes, we will emphasis on the boron, aluminum and phosphorus detection over several hundreds of micrometers. Such analysis should clarify the doping profile of SOS diodes.

II. EXPERIMENTAL

The SIMS analyses were performed with magnetic sector SIMS (IMS7f-CAMECA). For silicon, SIMS is usually performed in order to measure the depth distribution of dopants (boron or phosphorus) and contaminants (as hydrogen) in the material. In routine analysis, the pressure in the analysis chamber is in the range of $2 - 6 \times$

10^{-10} mbar. The depth of the resulting SIMS crater is measured with a Dektak8 (Bruker) step-meter.

A. Standard SIMS conditions

As the SIMS technique is mostly used in silicon to detect impurities, measurements are performed with parameters allowing high sensitivities. In the case of boron and aluminum detection, the O_2^+/M^+ configuration is employed: primary ions with an O_2^+ source and detection of positive secondary ions of mass M . The energy of the O_2^+ primary beam is set to 15 keV. The raster size is $150 \times 150 \mu\text{m}^2$ and the analyzed zone is restricted to a diameter of $33 \mu\text{m}$ to limit crater edge effect. Secondary ions are detected in the positive mode by biasing the sample to +5000 V, leading to an interaction energy of the primary ions of 10 keV and an incidence angle of 37° with respect to the normal of the sample. The analyses are performed at low mass resolution, $M/\Delta M \sim 400$, to have a maximum sensitivity. The detected masses are the one coming from the matrix, $^{30}\text{Si}^+$, and the one coming from the dopant impurities, $^{11}\text{B}^+$ and $^{27}\text{Al}^+$.

In the case of phosphorus detection, the Cs^+/M^- configuration is employed: positive primary ions with a Cs^+ source and detection of negative secondary ions of mass M . The energy of the Cs^+ primary beam is set to 10 keV. The raster size is $125 \times 125 \mu\text{m}^2$ and the analyzed zone is restricted to a diameter of $33 \mu\text{m}$ (as for O_2^+/M^+ configuration). Secondary ions are detected in the negative mode by biasing the sample to -5000 V, leading to an interaction energy of the primary ions of 15 keV and an incidence angle of 23° with respect to the normal of the sample. With low mass resolution SIMS analysis, the 31 amu signal contains $^{31}\text{P}^-$ (30.974 amu) with all mass interferences as $^{30}\text{Si}^1\text{H}^-$

(30.982 amu) and $^{29}\text{Si}^1\text{H}_2^-$ (30.992 amu). The $^{31}\text{P}^-$ mass is then not clearly distinguishable from neighboring masses. Fortunately, our apparatus allows to work at high resolution ¹⁴, that is to say to separate $^{31}\text{P}^-$ from its neighboring ions. The adjustment consists of slightly closing the entrance and exit slits of the spectrometer, just enough to get $M/\Delta M$ close to 4 000. It is worth noting that the use of high mass resolution (HMR) settings comes at the expense of sensitivity during the SIMS analysis. The detected masses are the one coming from the matrix, $^{30}\text{Si}^-$, the one coming from the dopant impurity, $^{31}\text{P}^-$ and the one from the mass interference, $^{30}\text{Si}^1\text{H}^-$.

The standard SIMS conditions are commonly used to get the distribution of impurities through the volume of a given sample. The analysis is performed from the top surface of the sample in direction of the bottom and over just a few micrometers into the sample. In the case of the SOS diode, the total thickness of 4 dies to analyze is around 1 500 μm , making our standard SIMS conditions unusable.

B. Line scan mode

A line scan in our SIMS apparatus consists in displacing the stage holder along the X axis from an initial position to an ending position. At the initial position and after each displacement, the intensities of the elements are recorded during a certain amount of time (see Figure 1). The resulting profile presents intensity values (in cps) as a function of the displacement along the sample (in μm).

In our study, the total scan length is 1150 μm and the displacement step is 2 μm . Thus, the total measuring points is of 575. To get enough lateral resolution, the analyzed zone is restricted to a diameter of 8 μm . For the O_2^+/M^+ and Cs^+/M^- configurations, we

use primary intensities of 500 nA and 60 nA, leading to sputtering rates, S_r , of 8 nm/s and 2 nm/s in silicon matrix, respectively. In the case of O_2^+/M^+ condition, the time per point is fixed to 2 s for $^{11}B^+$ and $^{27}Al^+$ and 1 s for $^{30}Si^+$, leading to a line scan duration of around 1h30. In the case of Cs^+/M^- condition, the time per point is fixed to 4 s for $^{31}P^-$ and 1 s for matrix ions ($^{30}Si^-$ and $^{30}Si^1H^-$), leading to a line scan duration of around 1h45.

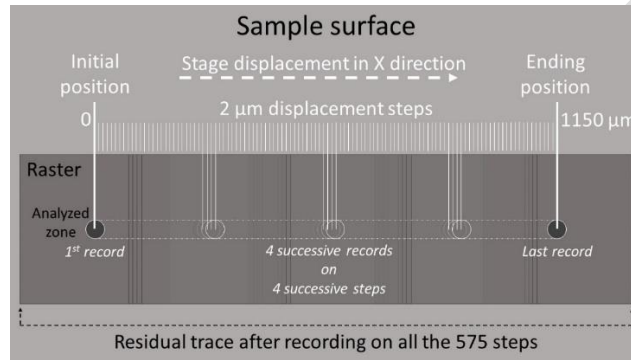


FIG. 1. Schematic view of the line scan performed by SIMS.

While conventional SIMS analysis generally requires little sample preparation, it is not the same for line scan analysis, which requires specific and careful sample preparation. This preparation is described in the following part.

C. Sample preparation

We studied an SOS diode rated for 3 kV and 1 kA that was provided by the Institute of Electrophysics of the Russian Academy of Sciences. The diode is composed of four identical silicon dies (~400 μm width, 0.25 cm² area) brazed in series using tin and lead based alloy. The anode and cathode terminals of the stack are made of two metal discs: molybdenum for the anode and copper for the cathode. The edge termination of

each die is made by positive beveling; the edge of the stack is insulated with a dielectric compound.

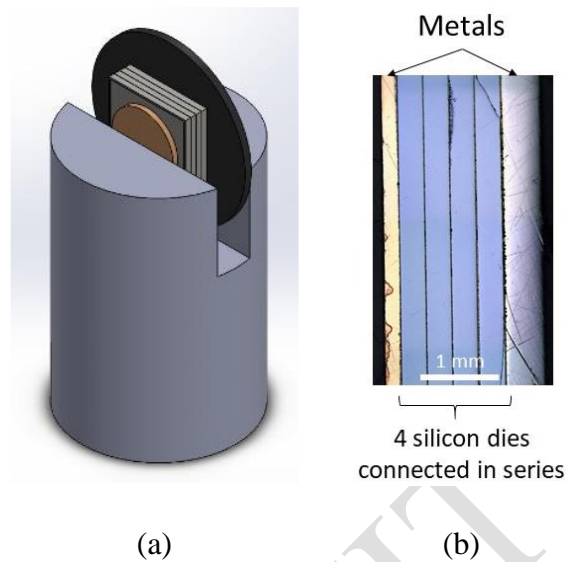


FIG. 2. (a) Illustration of the sample fixed in its holder 16; (b) Image of the sliced SOS diode after its cutting and polishing to get a mirror-like surface.

The sample preparation has been conducted within the Platform “I3” (Inorganic Isotopic Imaging) of the IPREM (Institut des Sciences Analytiques et de Physico-Chimie pour l’Environnement et les Matériaux) of the University of Pau (UPPA). The diode was fixed with epoxy resin in a cylindrical plastic holder with a diameter compatible with the sample manipulation system of the SIMS instrument (see Fig.2 (a)). To reveal the internal structure of the diode, it was cut (perpendicular to the die surface) with a diamond wire cutting tool. The surface was mechanically polished using polishing compounds with gradually decreasing grain sizes down to 1 μ m. The diode was cleaned by solvent in ultrasonic wave bath after each change of the polishing compound. Surface quality control was performed visually using an optical microscope. A gold layer of about

50 nm thickness was further deposited on the polished surface to have a conductive surface of the sample. As a result, the diode was prepared to get a conductive mirror-like surface, compatible with SIMS requirements (see Fig.2 (b)).

D. Quantification and detection limit

To quantify an element in the depth of a material, it is necessary to analyze a reference sample. Such reference sample is usually made of the material (here silicon) and specifically implanted with a known ion fluence of the requested element (boron, aluminum and phosphorus in our case) ¹⁵. The SIMS analysis of the reference samples allows the determination of the relative sensitivity factor of the element to quantify the element of interest and the detection limit of this element. Note that the quantification is based on knowledge of the implanted dose which is given by the implanters to within 10%.

TABLE I. Detection limits, DL, in silicon under our standard SIMS conditions with an analyzed zone restricted to a diameter of 8 μm .

<i>Element</i>	¹¹ B	²⁷ Al	³¹ P
<i>Ion fluence (at/cm²)</i>	1.07x10 ¹³	1.0x10 ¹⁴	1.0x10 ¹⁴
<i>Ion energy (keV)</i>	200	150	150
<i>DL (at/cm³)</i>	5.0 x 10 ¹⁵	1.0 x 10 ¹⁴	3.5 x 10 ¹⁶

The detection limits of boron, aluminum and phosphorus are reported in Table I. Those values are reached at the time of the analyses and under the SIMS analysis

conditions given in section II.A.1., except for the analyzed zone that is restricted to a diameter of 8 μm , as for the line-scan mode.

III. RESULTS AND DISCUSSION

A. *Raw profiles*

Figure 3 (a) and Figure 4 (a) show the pictures of the trace left by the line scan analysis under O_2^+/M^+ and Cs^+/M^- SIMS conditions, respectively. We observe that the starting position of the traces is in the first left side die (Die 1), from the anode side, while the ending position is in the fourth right side die (Die 4), from the cathode side of the SOS diode. We also see that the traces are perpendicular to the interfaces between dies. Thus, the resulting raw profiles (see Figures 3 (b) and 4 (b)) describe properly the distribution of elements from the inside of Die 1 up to the inside of Die 4 while crossing Die 2, Die 3 and three die interfaces (Die 1 – Die 2, Die 2 – Die 3 and Die 3 – Die 4). Die 2 and die 3 are analyzed over their entire thickness.

As expected, the matrix signals on the raw profiles are constant inside each die (see Figures 3 (b) and 4 (b)). As the dies are connected together with no-silicon alloy, the matrix signals on the raw profiles drop down at each of the three die interfaces.

From the raw profiles, we can observe that all dies present similar depth-distributions for each dopant (boron, aluminum and phosphorus). Let's focus on Die 2 to describe each dopant distribution from the anode side (Die 1 – Die 2 interface) to the cathode side (Die 2 – Die 3 interface).

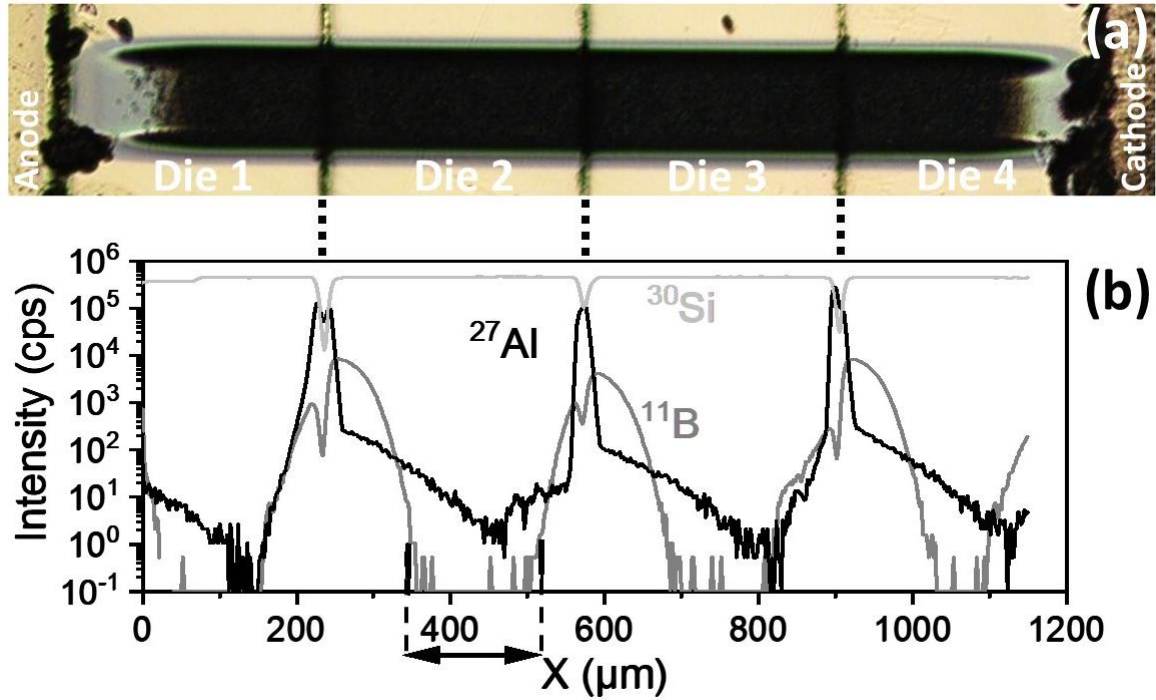


FIG. 3. Line scan analyzed in O_2^+/M^+ SIMS conditions. (a) Image of the trace left on the sample at the end of the analysis. (b) Raw profile obtained at the end of the analysis with boron (^{11}B) and aluminum (^{27}Al) dopant signals, together with the silicon matrix signal (^{30}Si). The interfaces between dies are superimposed with the minimum intensity of the matrix signal.

In Figure 3 (b), boron signal presents first, on the anode side, a bump with value starting at around 10^4 cps and decreasing down to 0 (i.e. undetectable boron in our analysis conditions) over ~ 105 μm . After ~ 160 μm (materialized by a double arrow) with zero signal, a second boron bump is observed starting around 265 μm in the die and reaching, after ~ 50 μm , a maximum value of $\sim 10^3$ cps on the cathode side.

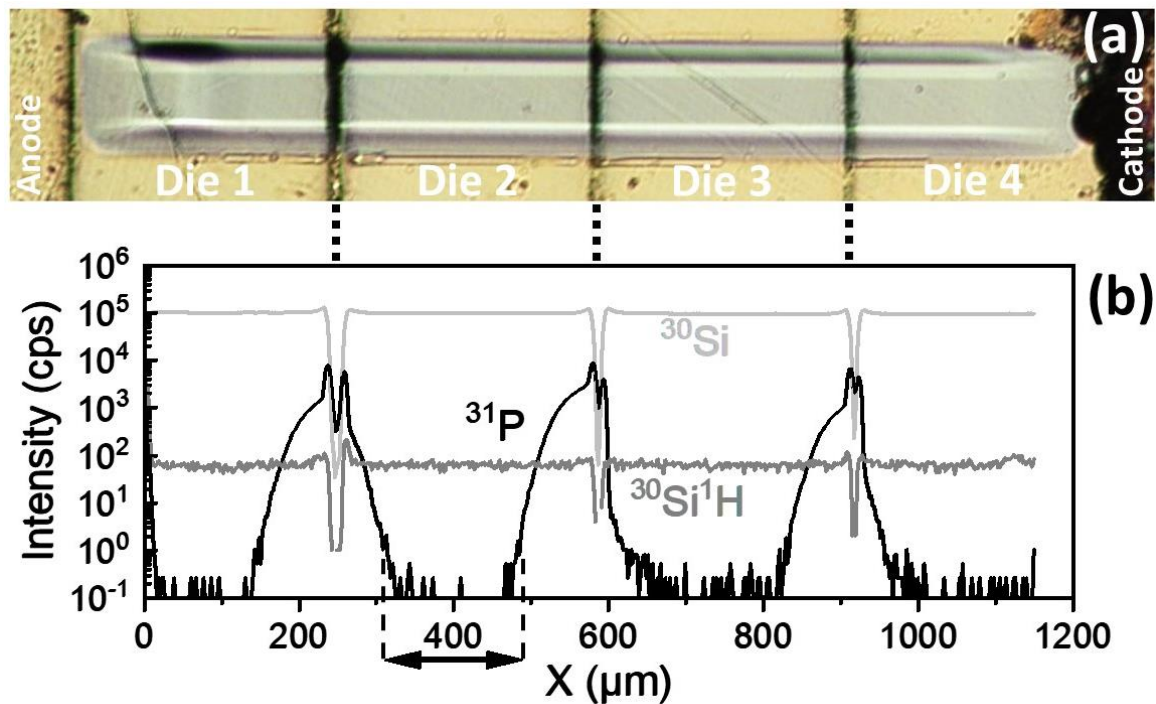


FIG. 4. Line scan analyzed in Cs^+/M^- SIMS conditions. (a) Image of the trace left on the sample at the end of the analysis. (b) Raw profile obtained at the end of the analysis with phosphorus (^{31}P) together with the silicon matrix signals (^{30}Si and $^{30}\text{Si}^1\text{H}$). The interfaces between dies are superimposed with the minimum intensity of the matrix signals.

For the aluminum signal, we observe on the anode side, first, a peak at high intensity ($\sim 10^5$ cps) that drops down from 3 decades within ~ 10 μm , followed by a smooth decrease of 2 decades over the next ~ 210 μm before an increase of 1 decade within ~ 100 μm on the cathode side. Then, a peak is observed in the last 10 μm of the die, with a maximum intensity value in the same range of the anode side peak.

From the phosphorus signal (see Figure 4 (b)), we observe first, on the anode side, a peak with high intensity ($\sim 10^4$ cps) that drops down from nearly 2 decades within ~ 7 μm , followed by a decrease of 3 decades over ~ 57 μm , up to zero signal. After ~ 160 μm

(materialized by a double arrow) with zero signal (meaning at $\sim 224 \mu\text{m}$ in the die), the signal increases up to a few 10^3 cps within $90 \mu\text{m}$. At $\sim 314 \mu\text{m}$ in the die, on the cathode side, a peak appears in the last $\sim 8 \mu\text{m}$ with a maximum intensity in the same range of the anode side peak.

With all previous observations, we see that the dopant distributions are well described all along the die thickness that is estimated around $325 \mu\text{m}$. While signal is lower than 1 cps inside the die, the distribution of elements cannot be determined. As a result, boron and phosphorus distributions are still unknown within $\sim 160 \mu\text{m}$ interval (materialized by double arrows in Fig.3 (b) and Fig.4 (b)): in the ranges of $\sim 100 - 265 \mu\text{m}$ and $\sim 65 - 220 \mu\text{m}$ into the die, respectively.

B. Quantified profiles

Figure 5 (a) presents the quantification of the raw profiles focus on Die 2. We notice that the experimental profiles partially matched with theoretical doping profiles¹⁰ that are reproduced in Figure 5 (b). From SIMS profiles, the maximum values are $4.0 \times 10^{19} \text{ at/cm}^3$ for [B], $1.0 \times 10^{19} \text{ at/cm}^3$ for [Al] and $2.0 \times 10^{20} \text{ at/cm}^3$ for [P]. Those measured boron and phosphorus values are higher than the theoretical ones ($1.0 \times 10^{19} \text{ at/cm}^3$) while the experimental aluminum value in the tail is lower by ~ 1 decade than the one expected from theory. The higher experimental values might be due to the fact that SIMS analysis gives access to the atomic content while the theoretical profiles present acceptor and donor contents (N_a and N_d , respectively). Then, due to compensation process, N_a and N_d can be lower than the corresponding dopant concentrations. Another difference is the presence of phosphorus on the anode side that is not expected from

theory, as well as the boron and aluminum presence on the cathode side. For the presence of phosphorus on the anode side, one can suspect signal coming from either the phosphorus peak on the cathode side of the previous die, either the no-silicon alloy of unknown composition.

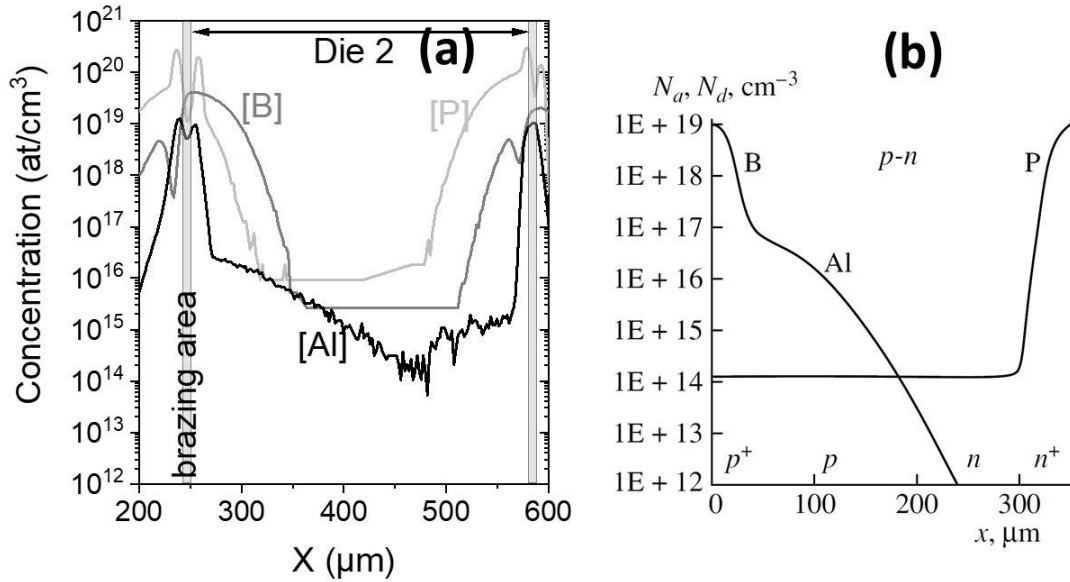


FIG. 5. (a) Quantified SIMS profile of the SOS diode showing the evolution of the boron, aluminum and phosphorus content. (b) Reprint of the theoretical doping profiles of the SOS diode from ¹⁰ showing the evolution of the carrier concentrations induced by boron, aluminum and phosphorus.

The minimum values are, as expected from the analysis, in the range of the detection limits: $\sim 10^{15}$ at/cm³ for boron, $\sim 10^{14}$ at/cm³ for aluminum and $\sim 10^{16}$ at/cm³ for phosphorus. This means that the plateaus seen at low values are at the detection limit values and the element distributions are then unknown in such regions. As explained

previously, the distributions of boron and phosphorus are currently unknown over ~ 160 μm in the die.

From the measured depth distributions, it is difficult to determine the exact position of the p-n junction into the dice that is a fundamental characteristic usually determined by measuring the breakdown voltage of the diode on an electronic equipment.

IV. SUMMARY AND CONCLUSIONS

By using dedicated SIMS conditions depending of the tendency of elements to produce positive or negative secondary ions, we have set line scans over 1150 μm range across a SOS diode. We show our capability to measure the depth distribution of dopants over several hundreds of micrometers with 2 μm step, with a sufficient lateral resolution. Keeping in mind all above observations, SIMS is a useful tool to analyze SOS diodes and to extract the depth distribution of elements that might be use in simulation programs. In future work, we will try to improve the lateral resolution by lowering down as much as possible the diameter of the analyzed area. This will allow a better description of the interfaces between each die. Moreover, a better knowledge of the no-silicon alloy will also help to interpret results. To avoid possible contamination from the solder zone, we consider testing a single SOS die to verify the obtained doping profile. The methodology developed and tested in this work provides access to the analysis of semiconductor devices with a thick structure of more than 1000 μm , which are frequently used in power electronics and solid-state pulsed power domains. As results obtained for SOS diodes require further verification, we plan to study other SOS diode or even test a single die.

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AUTHOR DECLARATIONS

The authors have no conflicts to disclose.

DATA AVAILABILITY

Data are available at [10.5281/zenodo.15087814](https://zenodo.org/doi/10.5281/zenodo.15087814)

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