

Low cost high current metal ion source

Vladimir Romanov*, Edward Moore*, David Sporleder*, Joe Krasowski*, Neil Bassom*

*Axcelis Technologies, 108 Cherry Hill Drive, Beverly Massachusetts, USA 01915

vladimir.romanov@axcelis.com

Abstract—Non-traditional implant species such as Al, Ga, In, and Sn are becoming increasingly important in semiconductor manufacturing but are difficult to generate in conventional ion sources due to their low vapor pressures and lack of suitable gaseous precursors. Existing approaches, including vaporizers and sputter targets, add complexity and can negatively impact source performance and lifetime. This paper presents a simple, low-cost method for generating metal ion beams by melting source material directly within the arc chamber using ion-source plasma heating. The molten metal is contained within specially designed source components and reactively etched by halogen-containing gases to produce metal ions. Stable beam currents of 13 mA Al^+ , 26 mA In^+ , 8 mA Sn^+ , and 15 mA Ga^+ were achieved at 20 keV extraction energy. The results demonstrate a practical alternative to vaporizers for producing high-current metal ion beams.

Keywords— Metal ion source, high-current ion implantation, metal fluoride generation

I. INTRODUCTION

Ion implantation is widely used to introduce dopants into semiconductor substrates with precise control of dose, depth, and lateral distribution. The technique has become particularly important for wide-bandgap semiconductor devices, where demanding electrical requirements often necessitate specialized implantation processes.

The rapid growth of SiC power electronics has increased demand for high-current metal ion sources, in particular aluminum, which is an important p-type dopant in SiC [1]. At the same time, continued evolution of ion implantation technology has driven the need for improved source materials

and source architectures capable of delivering higher beam currents, improved stability, and longer operational lifetimes. The selection and delivery of source materials have become increasingly important factors in determining implantation productivity, beam purity, and cost of ownership [2].

Conventional metal-ion-generation approaches rely on gas-phase precursors, vaporizers, or sputter targets. However, many technologically important metals, including aluminum, gallium, and indium, lack suitable gaseous precursors. Alternative approaches based on sputtering or vaporizers introduce challenges associated with source stability, contamination, and limited source lifetime [3].

Some commercial high-current metal ion sources based on metal-halide generation have produced beam currents as high as 35 mA for Al^+ ions and enabled operation with a broad range of metallic species. Similarly, advanced vaporization approaches have demonstrated gallium beam currents exceeding 10 mA with extended operating lifetimes, highlighting the feasibility of using solid or liquid feed materials for metal ion generation [3,4]. Nevertheless, these approaches still require additional hardware complexity and may remain susceptible to contamination and maintenance challenges.

To overcome these remaining limitations, we developed a cost-effective hardware solution that uses the heat generated by the ion-source plasma to melt a controlled volume of metal directly within the arc chamber. The metal is contained in the repeller or side liners of the arc chamber. Once liquefied, the metal is efficiently etched by halogen-containing gases such as PF_3 , NF_3 , BF_3 , and SiF_4 .

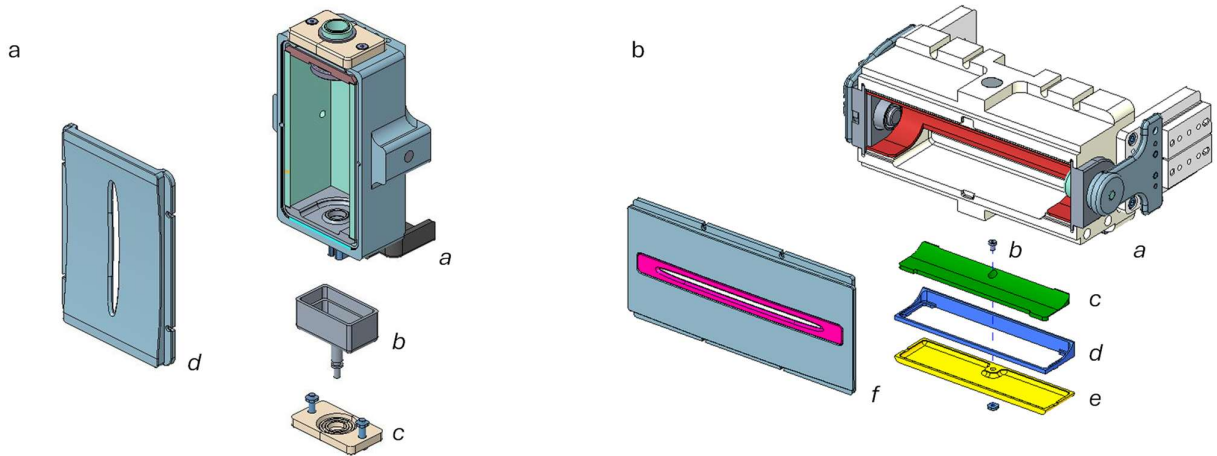


Figure 1. (a) Modified vertically oriented arc chamber: a – Arc chamber; b – Graphite repeller cup; c – Insulators with mounting screws; d – Arc slit. (b) Modified horizontally oriented arc chamber: a – Arc chamber; b – Mounting hardware; c – Tantalum lid with side cutouts designed for liquid gallium etching; d – Graphite insert/wicking barrier; e – Tantalum tray; f – Arc slit.

By combining a molten material delivery concept with advanced crucible design and multiple control strategies, the proposed system enables the use of ion species that are otherwise difficult to supply, while improving stability and beam-current control.

II. MATERIALS AND METHODS

All experiments with the modified vertically oriented arc chamber (Fig. 1a) were performed on an ion source test stand based on the Axcelis Optima HD single-wafer high-current platform [5]. All reactive gases (PF_3 , NF_3 , BF_3 , and SiF_4), as well as argon and hydrogen, used in this work were purchased from Linde and had a purity of 99.999%. The standard repeller was replaced with a rectangular graphite container having an internal volume of 10 cm^3 . The container was designed to prevent overflow of the molten metal and eliminate the risk of electrode shorting during operation.

The ion source architecture employs a crucible that retains the source material in a molten state directly within the arc chamber. The molten material is confined by gravity while exposing a controlled surface area to the plasma and reactive species, enabling efficient and stable release of metal-containing compounds into the gas phase for subsequent ionization and extraction.

Graphite was selected as the containment material because it exhibits poor wetting toward many liquid metals and can be surface textured to further increase the contact angle [6,7]. This minimizes spreading and wicking of the molten material, maintaining a stable, well-defined liquid surface area throughout operation. Compared with tungsten and alumina, graphite also provides a more stable liquid-metal interface because oxide layers on tungsten and alumina can participate in interfacial reactions that alter wetting behavior and reduce reproducibility [7]. Consequently, graphite offers a practical combination of non-wetting behavior, chemical compatibility, and electrical conductivity over the temperature range of interest.

Selected gallium experiments using NF_3 as the etching gas were performed in a modified horizontally oriented arc chamber (Fig. 1b) on an Axcelis Purion Dragon high-current test stand. The modified arc chamber incorporated a U-shaped liner assembly consisting of a tantalum lid with side cutouts designed to facilitate liquid gallium etching, a graphite insert that served as wicking barrier to restrict molten gallium migration, and a tantalum tray used to contain the liquid metal (Fig. 1b). This platform is capable of delivering extraction currents of up to 70 mA and provides extensive control of implantation conditions [8]. This ion source was used on a Purion Dragon™ high-current ion implanter to investigate gallium co-doping of SiGe:B as a promising approach for reducing contact resistivity in advanced semiconductor nodes [9].

III. RESULTS AND DISCUSSION

Fig. 2 compares the mass spectra obtained from a gallium-containing ion source operated with Ar, SiF_4/Ar , BF_3 , NF_3/H_2 , and PF_3 gas chemistries. All spectra were acquired at approximately the same source power ($\sim 1100 \text{ W}$), corresponding to a repeller temperature of $850\text{--}950^\circ\text{C}$ [10] at an ion source pressure of 1×10^{-5} to 2×10^{-5} Torr. In all cases, the spectra are dominated by the characteristic gallium isotopic peaks at $m/z \approx 69$ and 71 , corresponding to $^{69}\text{Ga}^+$ and $^{71}\text{Ga}^+$, indicating that elemental gallium ions remain the

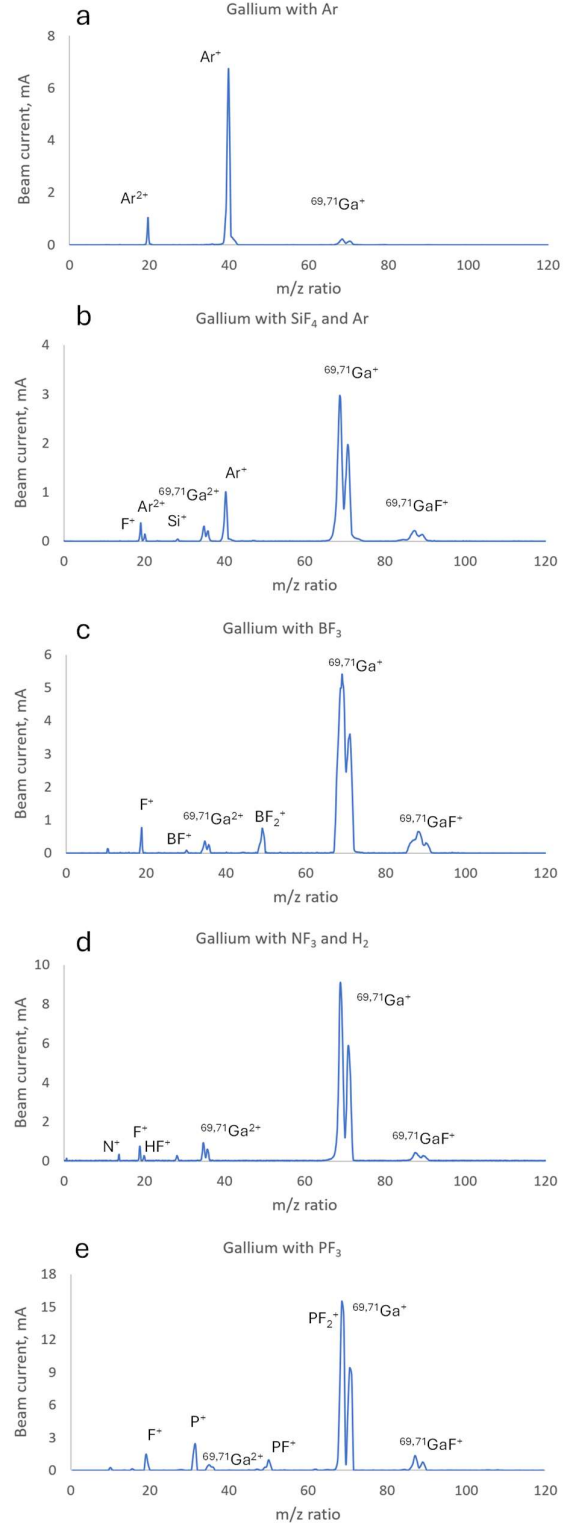


Figure 2. Mass spectra of gallium with argon as a sputter gas (a), with a mix of silicon tetrafluoride as an etching gas and argon (b), with a boron trifluoride (c), with a mix of nitrogen trifluoride and hydrogen (d), with a phosphorus trifluoride (e).

primary extracted species regardless of the process gas. During Ar-only operation (Figure 2a), the spectrum consists primarily of Ar^+ , Ar^{2+} , and several hundred microamps of Ga^+ beam current. Under these conditions, gallium is transferred to the gas phase mainly through thermal evaporation and plasma-assisted sputtering. This process is relatively inefficient because gallium vapor pressures of several millitorr require repeller temperatures approaching 1050 °C (Fig. 3) [11].

In contrast, the introduction of fluorine-containing gases significantly increased gallium ion production. Operation with a SiF_4/Ar mixture produced more than 3 mA of Ga^+ beam current (Fig. 2b). In addition, fluorine-based chemistries generated GaF^+ bands at $m/z \approx 88$ and 90, confirming the formation of volatile gallium fluoride intermediates. The SiF_4/Ar plasma exhibited relatively weak GaF^+ signals together with Si-containing fragments, suggesting limited fluorination of gallium under the investigated conditions. More pronounced fluorine chemistry was observed for BF_3 , NF_3/H_2 , and PF_3 plasmas (Figures 2c-e), which produced abundant fluorine-containing fragment ions, including F^+ , BF^+ , BF_2^+ , HF^+ , P^+ , PF_2^+ , and PF^+ . Correspondingly, the intensity of the GaF^+ and F^+ signals increased relative to the SiF_4/Ar case, indicating enhanced fluorination of the liquid gallium surface. Among the chemistries investigated, PF_3 and NF_3/H_2 produced the highest gallium ion currents while maintaining strong fluorine-related ion signals, highlighting differences in fluorine availability and plasma reaction pathways.

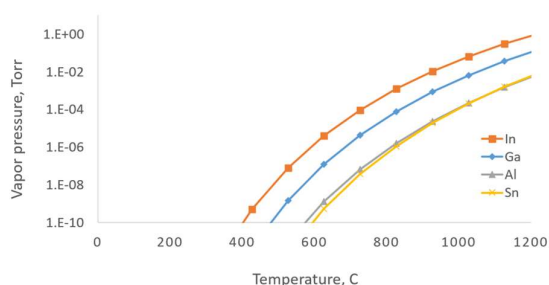


Figure 3. Modeled vapor pressures of In, Ga, Al and Sn as a function of temperature [11].

Life time experiments revealed significant differences among the fluorine precursors. Use of BF_3 as the etching gas resulted in complete suppression of the Ga^+ beam current after approximately 40 h of operation. GDMS analysis of deposits formed on the molten gallium surface confirmed substantial boron accumulation, indicating extensive BF_3 decomposition and incorporation of elemental boron into the liquid gallium. In contrast, no significant deposits were observed during PF_3 operation, despite the comparable solubility of phosphorus and boron in liquid gallium [12,13]. This behavior is attributed to the high volatility of phosphorus and the limited thermal stability of gallium phosphides relative to borides. Gallium phosphides are known to dissociate at elevated temperatures, releasing elemental phosphorus, whereas boron-containing compounds are significantly more stable [14,15]. Furthermore, phosphorus has a boiling point of 280 °C,

compared to 4000 °C for boron. At the operating temperature of the gallium reservoir (~900 °C), phosphorus-containing species are therefore expected to volatilize rather than accumulate. This interpretation is consistent with solid analysis showing phosphorus concentrations several orders of magnitude lower than boron. The accumulation of boron and formation of stable boron-containing phases likely explain the progressive source deactivation observed with BF_3 , whereas PF_3 operation does not produce comparable solid buildup.

The molten-metal fluorination approach was also

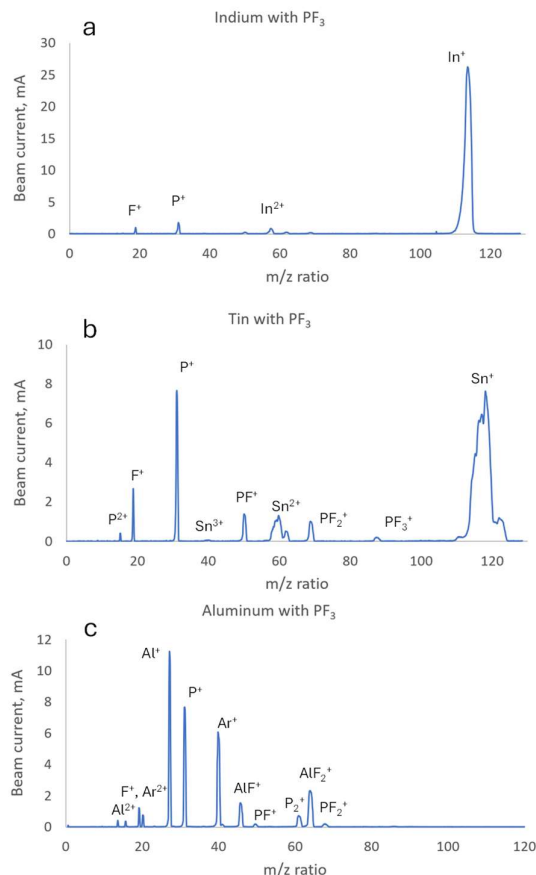


Figure 4. Mass spectra of phosphorus trifluoride with indium (a), tin (b) and aluminum (c).

evaluated for indium, tin, and aluminum using PF_3 as the fluorinating gas. Fig. 4 shows the corresponding mass spectra. Similar to gallium, the dominant extracted species were elemental metal ions, indicating efficient transport of the molten metal into the plasma through formation of volatile metal fluoride intermediates. Maximum ion beam currents of 26 mA In^+ , 8 mA Sn^+ , and 13 mA Al^+ were obtained under optimized operating conditions, demonstrating the applicability of the method across a broad range of metallic species. Stable operation exceeding 100 h was demonstrated at beam currents of 17 mA In^+ , 5.2 mA Sn^+ , and 11 mA Al^+ .

As illustrated in Fig. 4, PF_3 undergoes extensive fragmentation in the plasma, generating species such as PF_2^+ that coincide with the $^{69}\text{Ga}^+$ signal. Consequently, NF_3 was selected as the fluorinating gas to ensure interference-free operation at high Ga^+ beam currents over extended periods.

Hydrogen was added to control the halogen cycle within the arc chamber through the formation of volatile HF species [16]. Process parameters were subsequently optimized using the NF_3/H_2 chemistry. Under these conditions, stable operation was demonstrated for more than 280 h at a Ga^+ beam current of 7 mA without interruption or measurable source degradation.

Based on measured metal consumption rates, projected source lifetimes exceed 400 h for Ga^+ and In^+ and 180 h for both Sn^+ and Al^+ operation.

These results demonstrate that fluorine-containing gases promote the formation of volatile metal fluoride species, enhancing metal transport into the plasma and enabling sustained high-current metal ion beam generation.

IV. CONCLUSION

A simple and low-cost method for generating high-current metal ion beams was demonstrated by melting source materials directly within the arc chamber and using fluorine-containing gases to promote formation of volatile metal fluorides. The approach eliminates the need for vaporizers while maintaining stable source operation. Gallium experiments showed that fluorination significantly enhances metal transport compared with thermal evaporation alone, increasing extracted beam currents by more than an order of magnitude. Among the fluorinating gases investigated, PF_3 and NF_3/H_2 provided the highest sustained gallium currents, whereas BF_3 led to source degradation due to boron accumulation in the molten metal. The technique was further extended to aluminum, indium, and tin, producing beam currents of 13 mA Al^+ , 26 mA In^+ , 8 mA Sn^+ , and 15 mA Ga^+ , offering a practical and scalable alternative to conventional vaporizer-based metal ion sources.

ACKNOWLEDGMENT

The authors gratefully acknowledge Dr. Udo Verkerk for his expert guidance and helpful discussions on the chemistry aspects of this study.

REFERENCES

- [1] A. Hallén and M. K. Linnarsson, "Ion implantation technology for silicon carbide," *Surf. Coat. Technol.*, vol. 306, pp. 190-193, 2016.
- [2] P. Singer, "Source Materials Enable the Evolution of the Ion-Implantation Process," *Semiconductor Digest*, Feb. 2020.
- [3] T. Matsumoto et al., "High-current metal ion source for material modification in the semiconductor manufacturing processes," *MRS Advances*, vol. 10, pp. 188-192, 2025.
- [4] S. Ninomiya and Y. Kawasaki, "Novel vaporization method for gallium ion generation," *MRS Advances*, vol. 10, pp. 184-187, 2025.
- [5] P. Splinter, M. Graf, et al., "Optima HD: Single Wafer Mechanical Scan Ion Implanter," *Proc. 16th Int. Conf. Ion Implantation Technology (IIT 2006)*, pp. 601-604, 2006.
- [6] J. V. Naidich, "The Wettability of Solids by Liquid Metals," in *Progress in Surface and Membrane Science*, Vol. 14, D. A. Cadenhead and J. F. Danielli, Eds. New York, NY, USA: Academic Press, 1981, pp. 353-484.
- [7] N. Eustathopoulos, M. G. Nicholas, and B. Drevet, "Wettability at High Temperatures", *Pergamon Materials Series*, Vol. 3. Amsterdam, The Netherlands: Pergamon/Elsevier, 1999, p. 108.
- [8] J. DeLuca and G. Cai, "Single implant damage accumulation and interactions between multiple implants," *MRS Advances*, vol. 7, pp. 1358-1363, 2022.
- [9] J. Prominski et al. "Contact module engineering for advanced CMOS nodes at low thermal budget by Gallium and Germanium co-implant", *IIT 2026*.
- [10] V. Romanov, P. Silverstein, W. Platow, et al., "Low metals ion source," *MRS Adv.*, vol. 10, pp. 505-510, 2025.
- [11] Institute of Applied Physics, TU Wien, "Vapor Pressure Calculator"
- [12] C. Guminski, "Solubility of metals in liquid low-melting metals," *Z. Metallkd.*, vol. 81, pp. 105-110, 1990.
- [13] B. Onderka, J. Wypartowicz, and K. Fitzner, "Interaction between oxygen and phosphorus in liquid gallium," *Arch. Metall.*, vol. 36, pp. 5-12, 1991.
- [14] K.A. Gingerich, "Stability and vaporization behavior of group IV-VI transition metal monophosphides", *Nature*, 200, 877 (1963).
- [15] C.D. Thurmond, "Phase equilibria in the GaAs and the GaP systems", *J. Phys. Chem. Solids*, 26, 785-802 (1965).
- [16] T.-J. Hsieh and N. Colvin, "Improved Ion Source Stability Using H_2 Co-Gas for Fluoride-Based Dopants," in *Proc. 20th International Conference on Ion Implantation Technology (IIT 2014)*, Portland, OR, USA, 2014, pp. 1-4.