



Study of a liquid metal field ion emitter for the production of Si ions

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Abstract

The study of AuSi liquid metal alloy ion sources (LMAIs) for the production of Si ions is not new. However, the present work encompasses in a concise form almost all fundamental aspects of source behaviour, in particular of a Au₈₂Si₁₈ source. A key finding, manifested in the behaviour of the ion extraction voltage with temperature, is the abnormal behaviour of the surface tension coefficient of the alloy with temperature. An important deduction, however, concerns the mechanisms responsible for the creation of doubly charged ions: reasons of self-consistency suggest that while Si⁺⁺ is directly field-evaporated, Au⁺⁺ must form by the post-ionization of Au⁺.

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1. Introduction

Focused Si ion beams are useful for direct write applications, such as lithography on Si substrates without substrate contamination. However, as we shall see later, Si ions producing sources emit these ions mostly in a doubly charged state. This means that a given ion energy can be achieved with half the accelerating voltage that would be required for singly charged ions.

Si tends to react chemically with the needle substrate and this is the reason why Si liquid metal ion sources (LMISs) usually employ a suitable alloy containing Si. The Si ions are subsequently mass-separated from the beam, in the present case by an E×B filter. In this work we use a Au₈₂Si₁₈ eutectic with a melting point of 365 °C.

Fig. 1 shows a current–voltage ($i-V_0$) curve of the source. The curve is steeply rising, typical of well wetted, well roughened or grooved needles. The voltage has to be raised by ~2% above the source starting (V_{OC}) or extinction (V_{OX}) voltage to reach 30 μA emission current. In other words, $V_0 \simeq V_{OX} \simeq V_{OC}$, with [1]

$$V_{OC} \propto \gamma^{1/2} \quad (1)$$

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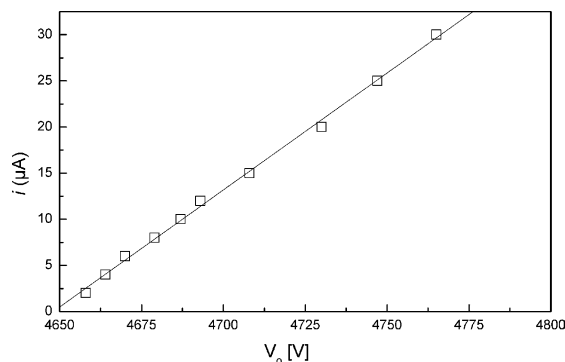


Fig. 1. Current–voltage ($i - V_O$) characteristics of $\text{Au}_{82}\text{Si}_{18}$ source for $T = 730$ °C.

γ being the surface tension coefficient of the liquid metal, or alloy. With most elemental sources and some liquid metal alloy ion sources (LMAISs), γ decreases linearly with temperature (T), which is translated into a similar behaviour [2] of V_O , provided changes in γ are small – as they normally are [3]. This is not the case, however, with the alloy under consideration. From Fig. 2 it is seen that V_O , i.e. γ , at first increases, reaches a broad maximum and then it decreases. This behaviour was first reported with a $\text{Au}_{77}\text{Ge}_{14}\text{Si}_9$ source [2] (Fig. 2) and an explanation was given then, in terms of a residual crystalline structure at the surface of the liquid alloy. The rising portion of the curve corresponds to low entropy states and the first few atomic layers of the surface of such a liquid metal are virtually crystalline. At sufficiently high temperatures, however, this remaining order is destroyed. That is,

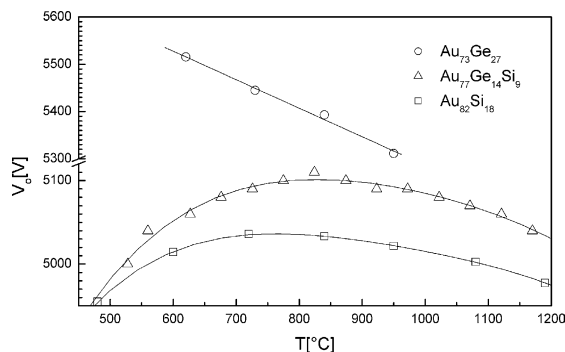


Fig. 2. Extraction voltage (V_O) versus emitter temperature (T) for $\text{Au}_{73}\text{Ge}_{27}$, $\text{Au}_{77}\text{Ge}_{14}\text{Si}_9$ and $\text{Au}_{82}\text{Si}_{18}$ LMIS. Current, $i = 10$ μ A.

the surface becomes thermally delocalized and γ reverts to the familiar monotonic decrease with temperature. This phenomenon has also been observed with pure metals, such as Cu, Zn and Co [4].

From Fig. 2 we can see that the $\text{Au}_{73}\text{Ge}_{27}$ source behaves like most pure metals, displaying a linear decrease of V_O with T . It would, therefore, appear that the presence of Si is responsible for the abnormal behaviour of γ with T , in the case of the $\text{Au}_{82}\text{Si}_{18}$ and $\text{Au}_{77}\text{Ge}_{14}\text{Si}_9$ sources. We now turn our attention to the mass spectrum of the source (Fig. 3). It can be seen that the dominant species are Au^+ , Si^{++} , Au^{++} and Si^+ , in that order. The main Si^{++} peak is due to the ^{28}Si isotope and the small peaks adjacent to it are due to ^{29}Si and ^{30}Si . The peaks to the left of the Au^+ peak are mainly due to Au clusters, Au ($n = 1-5$), clearly discernible in more sensitive measurements; here we shall be dealing with the main species only, as well as the mechanisms responsible for their creation.

Fig. 4 shows the ratio of the abundance of the doubly charged to singly charged monoatomic ions in the beam as a function of emission current.

It is seen that due to space-charge stabilization of the apex field [5,6], above 10 μ A I^{++}/I^+ remains essentially constant. In Table 1, where the evaporation fields, as well as the fields for post-ionization (E_{pi}) are shown for both Au and Si, note that $E_{\text{Si}^{++}} < E_{\text{Si}^+}$ indicating, according to Brandon's criterion [8], Si^{++} will dominate in the beam, and this is in fact the case. Also, the consistency of E_{pi} for Au and $E_{\text{Si}^{++}}$ we take as evidence that while Si^{++} is directly field evaporated, Au^{++} forms by the post-ionization of

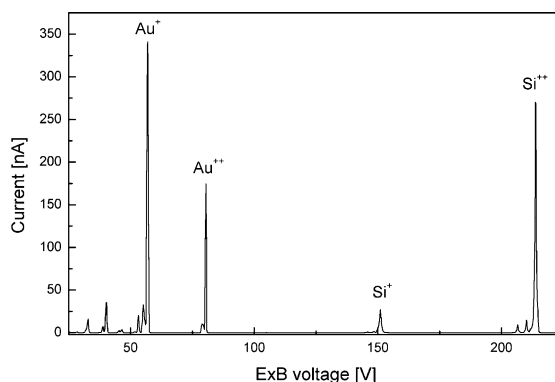


Fig. 3. Mass spectrum of $\text{Au}_{82}\text{Si}_{18}$ source. $i = 15$ μ A.

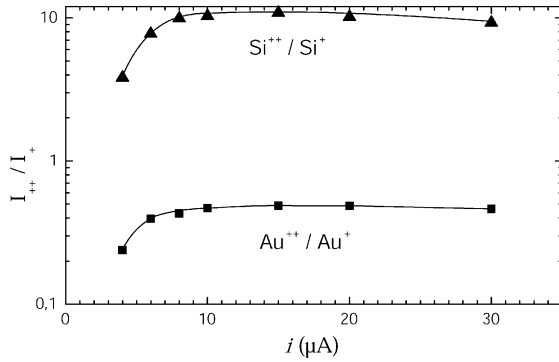


Fig. 4. Ratios of doubly to singly charged monoatomic ions of $\text{Au}_{82}\text{Si}_{18}$ source as a function of emission current i . $T = 850$ °C.

Table 1

Values of the evaporation fields calculated for singly (E^+) and doubly charged (E^{++}) ions for Au and Si; also shown are values for the post-ionization [7] from the singly to the doubly charged state (E_{pi})

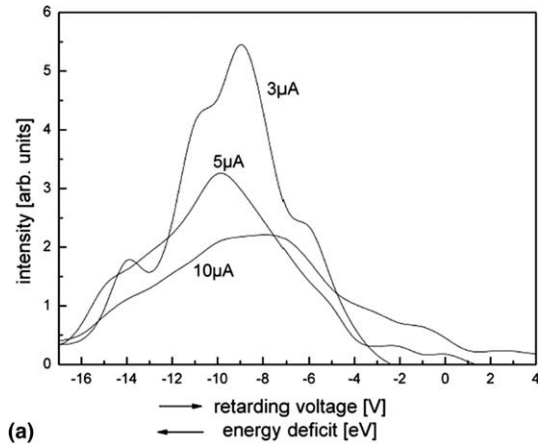
	Au	Si
E^+	4.8	4.5 (4.7)
E^{++}	5.0	3.3 (3.4)
$E_{\text{pi}} (\geq 10\text{A})$	3.5 [3.3]	2.3 [2.1]

Values in parentheses are given both by Brandon [8] and Ishitani et al. [9]. Values in square brackets from [15] and [16]. All field values are in $\text{V}/\text{\AA}$.

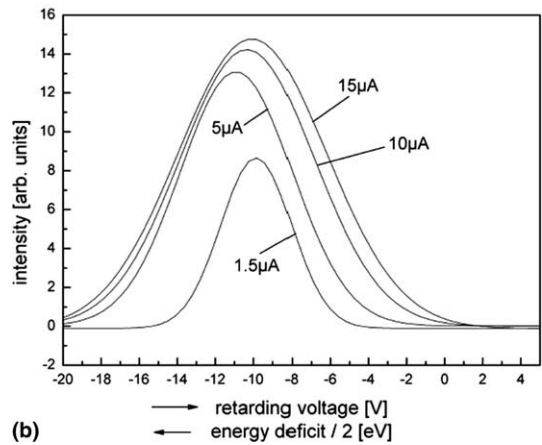
Au^+ . As a matter of fact, the field has only to change from 3.35 to 3.5 $\text{V}/\text{\AA}$ in order to achieve the constant value of $I^{++}/I^+ \simeq 0.5$ for Au (Fig. 4) [7].

Finally, we present energy distribution measurements for the Si^+ and Si^{++} ions (Fig. 5(a) and (b)). We can see that for Si^+ the curves are distorted as found by Swanson [10] with a $\text{Au}_{90}\text{Si}_{10}$ LMAs (m.p. 657 °C), for currents between 5 and 25 μA . In fact, the curve for 5 μA looks very much like Swanson's, although the width of his curve is larger than ours. Also, as with Swanson's results, the shoulder tends to disappear as the current is raised. However, our results for the energy spread ($\Delta E_{1/2}$) of Si^{++} are almost exactly the same as Swanson's (Fig. 6). Our results display a $\Delta E \propto i^{1/3}$ relationship, in close agreement with the Si^{++} results of our $\text{Au}_{77}\text{Ge}_{14}\text{Si}_9$ source [11]; the results of Swanson obey a $\Delta E_{1/2} \propto i^{0.4}$ law.

An explanation to consider for the nature of the secondary peaks, or shoulders in the energy distri-



(a)



(b)

Fig. 5. Energy distribution of Si^+ (a) and Si^{++} ions (b) versus emission current. $T = 734$ °C.

bution of Si^+ is a mechanism of field ionization at some distance from the emitter. However, there are serious difficulties with this explanation, due to insufficient heat input to the emitter to account for the necessary atom flux to be field-ionized [12] – unless the atoms are released from the break-up of larger ionic complexes or droplets, possibly by ion impact.

Table 2 shows the calculated peak energy deficits (ΔE_n), according to [13]:

$$\Delta E_n = A + \sum_n I_n - n\phi_C, \quad (2)$$

and compares them to these found experimentally for low currents. In Eq. (2) A is the binding energy (heat of evaporation) of the bound atom (subsequently ion); $\sum_n I_n$ is the sum of the ionization

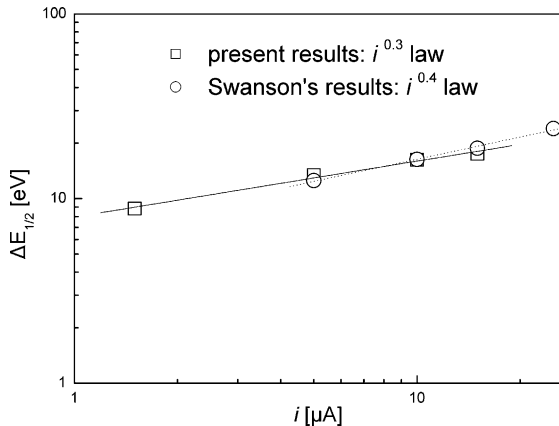


Fig. 6. Energy spread $\Delta E_{1/2}$ (FWHM) of Si^{++} ions versus i ; $T = 734$ °C (\square). Also shown results of Swanson's [10] $\text{Al}_{90}\text{Si}_{10}$ source (\circ); $T = 660$ °C. Note that Swanson's results refer to voltage rather than energy spread measurements, so that for doubly charged ions like Si^{++} they were multiplied by a factor of 2.

Table 2

Comparison of experimentally and theoretically obtained values of the peak energy deficit ΔE (eV) for Si^+ and Si^{++}

	$\Delta E(\text{exp})$	$\Delta E(\text{th})$
Si^+	8.90	7.9 (8.1)
Si^{++}	19.6	19.4 (19.4)

Values in parentheses are calculated from values of A and ϕ_C by Brandon [8] and Ishitani et al. [9].

potentials, if the atom is n -fold ionized; ϕ_C is the work function of the retarding electrode (4.9 eV for Ni) [14]. It is seen that the agreement between the predictions of Eq. (2) and experiment is rather satisfactory, strongly indicating a field evaporation mechanism for the creation of Si ions.

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