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ENERGY DISTRIBUTION OF ION BEAM FROM VARIOUS LIQUID METAL ION SOURCES

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ABSTRACT

We have precisely measured energy distributions of mass separated Si, Be, and B ion beams from various liquid metal (LM) alloy ion sources using Au-Si-Be, Pd-Ni-Si-Be-B, Al-Si, and Pt-Si alloys. It was found that singly charged ion species have long tails in both the higher and lower energy regions of the energy distribution at two orders of magnitude below the peak ion current intensity.

The higher energy ion tail can be explained by charge transfer collision between doubly charged ions and neutral atoms. The lower energy ion tail is caused by charge transfer collision and free space field ionization of neutral atoms.

It was found that the energy distribution of singly charged Si⁺ depends strongly on alloy systems. Si⁺ from the Pt-Si ion source exhibited no tails in the energy spectrum. We also discussed this phenomenon with the field dissociation model of Si cluster ions.

1. INTRODUCTION

Interest is growing in focused ion beam technology as means for semiconductor microfabrication and microanalysis. Liquid metal (LM) ion sources are used for this technology because of their high brightness and very small source area.

The energy distribution of emitted ions from the LM ion source is of importance because chromatic lens aberration limits the maximum current density of focused ion beams at a target. The tails of lower energy ions in the energy distributions, which were mentioned by Swanson et al.¹ and Sudraud et al.², cause a tail effect in the

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ion intensity profile of focused ion beams. The energy distribution also gives us the information on the ion formation mechanism. Although previous workers have measured energy distributions of LM ion sources\(^{3-7}\)), detailed measurements at two or three orders of magnitude below the peak ion current intensity have not yet been reported.

In this paper, we describe the results of energy distribution measurements of various LM alloy ion sources down to three orders of magnitude. The ion formation mechanism of singly charged ion species is also discussed.

2. EXPERIMENTAL

We investigated the energy distributions of LM ion sources with \(\text{Au}_{59}\text{Si}_{27}\text{Be}_{14}\), \(\text{Pd}_{51}\text{Ni}_{14}\text{Si}_{15}\text{Be}_{6}\text{B}_{24}\), \(\text{Al}_{86}\text{Si}_{20}\), and \(\text{Pt}_{77}\text{Si}_{23}\) alloys. These ion sources are particularly important for maskless ion implantation in III-V compound semiconductors such as GaAs\(^{10}\)) because they emit Si for n-type and Be for p-type ion species. An ion source consists of a reservoir and an emitter needle whose apex radius was several microns. They were resistively heated by carbon blocks which sandwich both the reservoir and the emitter.

The energy distributions of emitted ions were measured by use of a 60° sector magnet with a radius of 15 cm. The ion source voltage was fixed at 4 kV. The total ion emission current was controlled by a negatively biased extractor which maintained a constant source potential. The extracted ions passed through an entrance slit of the magnet whose width subtended an 8 mrad acceptance angle at the emitter. The energy resolution was less than 2.4 volts at a source potential of 4 kV. We calibrated the energy scale by the shift of the energy spectrum with definite increment of the source potential. The operating temperatures of ion sources were monitored by a spot pyrometer.

3. RESULTS AND DISCUSSION

Energy distributions of Si and Be ion beams from the Au-Si-Be ion source are shown in Figs. 1 and 2. The profiles of doubly charged \(\text{Si}^{++}\) and \(\text{Be}^{++}\) are very sharp and almost Gaussian. The energy distributions of singly charged ions, however, are broad with long tails which show subsidiary shoulders.
extending to several tens of volts at the level of one or two orders below the peak ion current intensity. While the lower energy ion shoulder for Si\(^+\) ions was observed by Swanson\(^3\)), we also observed tails of higher energy ions. Figure 3 shows the results for the singly charged ion species from the Pd-Ni-Si-Be-B ion source. They also exhibit long tails, Si\(^+\) having the largest. However, B\(^+\) has no higher energy ion tail.

We think that these tails are caused by several ion formation mechanisms in addition to field evaporation which is the main ion formation mechanism. As mentioned by Dixon\(^11\)) and Venkatesan et al.\(^12\)), charge transfer collision between ions and neutral atoms can be responsible for these tails. We think that the following processes are occurring in the area several tens of angstroms from the emitter apex, producing fast and slow singly charged ions.

\[
\begin{align*}
M^{++} + M &\rightarrow M^{+} + M^{+} \\
&\text{fast slow} \\
M^{+} + M &\rightarrow M + M^{+} \\
&\text{fast slow}
\end{align*}
\]

The fast singly charged ions which were converted from doubly charged ions are reaccelerated in the local field and finally detected in the mass spectrometer with an increased energy compared with normally accelerated field evaporated ions. The fast ions converted from doubly charged ions must correlate with the amount of doubly charged ions. This argument is supported with the experimental data shown in Fig. 3 and Table 1. Si\(^+\) has the largest higher energy ion tail and the ratio of Si\(^{++}/\)Si\(^+\) is also the largest, while B\(^+\) has no higher energy ion tail.

### Table 1: Ion flux ratio of M\(^{++}/\)M\(^+\).

<table>
<thead>
<tr>
<th>Ion Source</th>
<th>M(^{++}/)M(^+)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Pd-Ni-Si-Be-B</td>
<td>10</td>
</tr>
<tr>
<td>Au-Si-Be</td>
<td>1</td>
</tr>
<tr>
<td>Al-Si</td>
<td>5</td>
</tr>
<tr>
<td>Pt-Si</td>
<td>20</td>
</tr>
</tbody>
</table>

Fig. 2 Energy distribution of Si\(^+\) and Be\(^+\) ion beams from Au-Si-Be LM ion source.

Fig. 3 Energy distribution of Si\(^+\), Be\(^+\), and B\(^+\) ion beams from Pd-Ni-Si-Be-B LM ion source.
tail and doubly charged $B^{++}$ ions were hardly observed because of their large evaporation field.

Lower energy ion tails are likely explained by charge transfer collision producing slow ions and also free space field ionization in the dense cloud of neutrals several tens of angstroms out from the emitter apex\(^3\). Although the origin of the neutrals is not yet clear, the fact that emission of ions is accompanied by the emission of light from the region adjacent to the emitter apex suggests existence of a dense cloud of neutrals\(^{12,13}\). When the neutrals are generated at the ion emitting region, these released neutrals are immediately field ionized due to a sufficiently high electric-field such as to cause field evaporation. These field ionized ions can not be distinguished from field evaporated ions. Therefore neutral atoms may be generated at the side of the Taylor cone, some being attracted into the high field region. The results that the energy distributions of $Si^+$ and $Be^+$ from the Au-Si-Be ion source did not vary with operating temperatures between 500°C and 900°C suggest that the existence of Si and Be neutrals is not a result of thermal evaporation.

Ion emission properties of LM alloy ion sources are complicated and depend on alloy systems, as shown by Umemura et al. who studied the P ion emission from different alloys\(^{14}\) and Dixon who discussed impurity ion emission from a contaminated Ga ion source\(^{15}\). We have studied Si ion emission from various alloy ion sources. Figure 4 shows the energy distributions of singly charged $Si^+$ ions. The operating temperature of all sources was around 900°C. It is clear that the energy distributions are completely different. The tail for the Al-Si ion source is smaller than that for the Au-Si-Be ion source. As far as higher energy ion tails are concerned, this result agrees with the charge transfer collision model. The ratio of $Si^{+++}/Si^+$ for the Al-Si ion source is 5 and smaller than that for the Au-Si-Be ion source. The Pt-Si ion source exhibits no tails for either the higher or lower energy ions.

At present we suspect that Si neutrals are formed by field dissociation of Si cluster ions. As Tsong discussed the mass analysis of pulsed-laser stimulated field evaporation of $Si^{16}$, the Si cluster ions may be dissociated into smaller cluster ions, atomic ions, or neutrals by Coulomb repulsion. When the field for the ion emission is relatively high, dissociation
would be more prominent. This is supported by the fact that the Al-Si ion source emits a slight amount of Si cluster ions, while, the Au-Si-Be and Pt-Si ion sources do not emit any Si cluster ions. This is shown in Figs. 5(a), (b), and (c). The field for the Al-Si ion source is qualitatively assumed to be lower than that for the Au-Si-Be and Pt-Si ion sources from the ion flux ratio of $M^{++}/M^+$ in Table 1. (A larger ion flux ratio represents a higher field.) For the Al-Si ion source, dissociated Si neutrals may be slightly less than those for the Au-Si-Be and Pt-Si ion sources as suggested by the data in Figs. 5. These assumptions agree with the fact that the Al-Si ion source exhibits a smaller tail of lower energy ions than the Au-Si-Be ion source. When the Pt-Si ion source is used, the field is so strong that the field dissociated Si neutrals are immediately field ionized in a very limited area. It is possible that these field ionized ions do not cause any tails. Si cluster ions emitted from the Au-Si-Be ion source, whose field is relatively lower than that for the Pt-Si ion source, may be dissociated in a larger area. The field ionization of dissociated neutrals occurs subsequently in the gradually decaying potential. This would result in the large tails in the energy distribution.

4. CONCLUSION

We have measured the energy distributions of mass separated Si, Be, and B ion beams from Au-Si-Be, Pd-Ni-Si-Be-B, Al-Si, and Pt-Si LM alloy ion sources.

Fig. 5 Mass spectrums of (a) Au-Si-Be ion source, (b) Al-Si ion source, and (c) Pt-Si ion source.
sources at two or three orders of magnitude below the peak ion current intensity. The energy distributions of singly charged ions are broader and longer-tailed than those of doubly charged ions. Si$^+$ has the largest tails, while B$^+$ has no higher energy ion tail. The higher energy ion tail is explained by charge transfer collision between doubly charged ions and neutrals, producing both fast and slow ions. The fast ions are responsible for the higher energy ion tail. This mechanism is supported by the fact that the tails are correlated with the amount of doubly charged ions. The lower energy ion tail is due to slow ions produced by charge transfer collision and free space field ionization in the dense cloud of neutrals near the emitter apex.

The energy distributions of singly charged Si$^+$ ions from Au-Si-Be, Al-Si, and Pt-Si ion sources were all completely different. The Pt-Si ion source exhibits no tails of either higher or lower energy ions. These experimental results will be discussed more fully elsewhere from the viewpoint of the neutral's formation mechanism.

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