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Development of an Au–Dy–Si liquid alloy ion source for focussed ion beam implantation

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Abstract

A liquid metal ion source (LMIS) based on the $Au_{78.2}Dy_8Si_{13.8}$ alloy was developed for focussed ion beam implantation of Dy ions. The mass spectrum of the LMIS shows the presence of Si^{2+}, Si^+, Dy^{3+}, Dy^{2+}, Au^{2+}, Au^+, Au_3^{2+} and Au_2^+ ions. The Au–Dy–Si LMIS shows high stability and long time operational capacity. A simple calculational technique for eutectic compositions of ternary alloys for LMIS is suggested on the base of binary phase diagrams of the used elements. © 2002 Published by Elsevier Science B.V.

Keywords: Focused ion beam; Alloy liquid metal ion source; Ternary alloy; Dysprosium ions

1. Introduction

Focusing ion beam (FIB) systems are used for maskless ion implantation in electronic structure fabrication, microfabrication by microetching and deposition and ion beam lithography [1–3]. The increasing application of FIB implantation results in a need of new ions of different chemical elements in liquid metal ion sources (LMIS). The fast growing interest towards implantation of magnetic ions [4–6] in semiconductors increases the demand for alloys of such elements suitable for long time operation in LMIS. Dysprosium, possessing a large magnetic moment, represents such an element. However, its utilization in LMIS is complicated due to its high melting temperature of 1409 °C and high vapor pressure of 76.2 Pa at this temperature. One of the very promising systems is the ternary Au–Si system with a third element, in this case Dy. The basic advantages of such alloys are low melting temperature, high wetting characteristics of the needle surface and the reservoir and high resistance to oxidation [7]. The most popular alloy on this base is $Au_{70}Si_{15}Be_{15}$ widely used in FIB implantation of $A_{III}B_V$ semiconductors [3,8].

In this paper a simple calculational technique of ternary alloys for LMIS and results of investigations of an Au–Dy–Si liquid alloy ion source for focussed ion beam implantation are presented.

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2. Experiment

The alloy $Au_{78.2}Dy_8Si_{13.8}$ (atomic%) was produced by melting of a preliminary pressed mixture of Au, Dy and Si pieces in an arc discharge furnace in Argon atmosphere. In order to increase the homogeneity, the ingot was turned over with subsequent melting. In Fig. 1 an EDX spectrum of the fabricated alloy is shown. In the spectrum lines corresponding to all three elements can be observed, which gives evidence of formation of a ternary alloy. Then, the alloy was placed in a graphite crucible for the filling of the LMIS.

A hairpin construction of the emitter with a spiral reservoir, often used in LMIS, was fabricated of 0.2 mm Tungsten wire. Cleaning and needle fabrication was conducted according to the technique described in [3]. An overall view of a filled LMIS is presented in Fig. 2. To prevent wetting of the heating wires by the melted alloy the wires were covered by ceramic glue. Filling of LMIS was performed by dipping it into the crucible with the melted Au–Dy–Si alloy in a separated vacuum system "emitter maker" at a pressure of $<10^{-5}$ Pa. The wetting of Tungsten and the filling of the reservoir was performed without any problems as in the case of Au–Si–Be alloys.

After preliminary testing, the ion source was mounted in an EIKO-100 FIB system used for analysis of ion beam mass spectra by means of an ExB filter. The output current was collected by a Faraday cup.

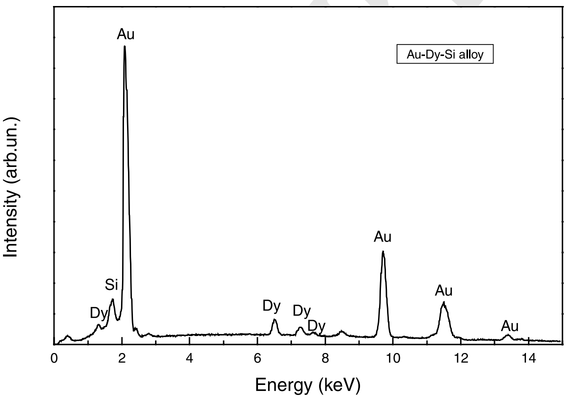

Fig. 1. EDX spectrum of the employed Au–Dy–Si alloy.

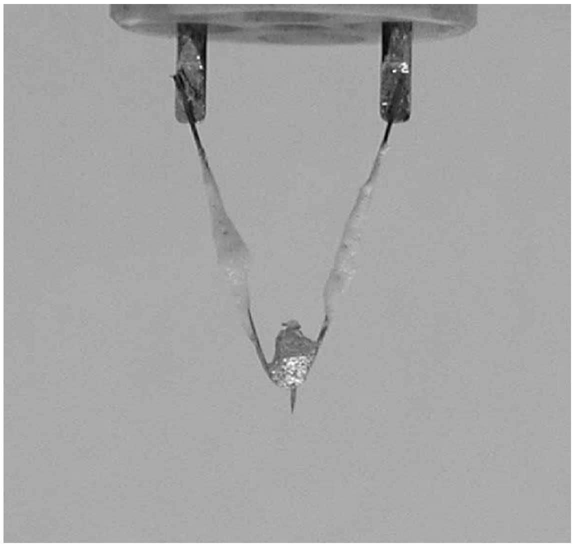

Fig. 2. Overall view of the filled Au–Dy–Si LMIS.

3. Results and discussion

3.1. Calculation of ternary alloy compositions for LMIS

Calculations of the Au–Si–Dy alloys were performed with the help of phase diagrams of binary alloys like Au–Si and Au–Dy, given in [9].

Suppose that a basic alloy consists of two completely miscible components A and B. In general, the most suitable binary alloys are those with a simple phase diagram and a single eutectic point. The change in Gibb's free energy related to an equilibrium melting of a component A in a narrow compositional interval near the eutectic point may by written as

$$\Delta G_{A\,\mathrm{melting}} = 0 \quad \text{or}$$
$$RT\ln\left(X_{A\,\mathrm{liquid}}/X_{A\,\mathrm{solid}}\right) + \Delta H_{A\,\mathrm{melting}} - T\,\Delta S_{A\,\mathrm{melting}} = 0, \tag{1}$$

where $\Delta H_{A\,\mathrm{melting}}$ and $\Delta S_{A\,\mathrm{melting}}$ are the melting related changes in the sum of standard and excess molar enthalpy and entropy of component A, re-

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spectively; $X_{A\,\mathrm{solid}}$ and $X_{A\,\mathrm{liquid}}$ are the molar fractions of the component A in the solid and liquid phase, respectively [10]. In the case of the Au–Si alloy

$$X_{\mathrm{Au\,solid}} = X_{\mathrm{Si\,solid}} = 1. \tag{2}$$

Similarly for the component B

$$\Delta G_{B\,\mathrm{melting}} = 0 \quad \text{or}$$
$$RT\ln(X_{B\,\mathrm{liquid}}/X_{B\,\mathrm{solid}}) + \Delta H_{B\,\mathrm{melting}} - T\,\Delta S_{B\,\mathrm{melting}} = 0. \tag{3}$$

The eutectic condition is given by

$$\Delta G_{A\,\mathrm{melting}} = 0 \quad \text{and} \quad \Delta G_{B\,\mathrm{melting}} = 0. \tag{4}$$

Empirical values of the parameters $\Delta H_{A\,\mathrm{melting}}$, $\Delta S_{A\,\mathrm{melting}}$, $\Delta H_{B\,\mathrm{melting}}$ and $\Delta S_{B\,\mathrm{melting}}$ may be found on the basis of A–B binary phase diagrams using a set of related values of T, $X_{A\,\mathrm{solid}}$, $X_{A\,\mathrm{liquid}}$ and T, $X_{B\,\mathrm{solid}}$, $X_{B\,\mathrm{liquid}}$ near the eutectic point and minimizing the least square deviations of the values of $\Delta G_{A\,\mathrm{melting}}$ and $\Delta G_{B\,\mathrm{melting}}$ from zero.

Applying a similar procedure for the A–C binary phase diagram, $\Delta H_{C\,\mathrm{melting}}$ and $\Delta S_{C\,\mathrm{melting}}$ may also be calculated.

The eutectic condition for three components is then defined by $\Delta G_{A\,\mathrm{melting}} = 0$, $\Delta G_{B\,\mathrm{melting}} = 0$ and $\Delta G_{C\,\mathrm{melting}} = 0$. Taking into account that for any ternary alloy

$$X_{A\,\mathrm{liquid}} + X_{B\,\mathrm{liquid}} + X_{C\,\mathrm{liquid}} = 1, \tag{5}$$

the eutectic values of $X_{A\,\mathrm{liquid}}$, $X_{B\,\mathrm{liquid}}$, $X_{C\,\mathrm{liquid}}$ and the eutectic temperature (T_{eutectic}) may be calculated.

In most cases, however, a composition of the ternary alloy with a fixed acceptable concentration of component C in the proximity of the eutectic point (i.e. $X_{C\,\mathrm{liquid}} = \mathrm{const}$) rather than the exactly ternary eutectic composition of the alloy is needed. In this case, $X_{C\,\mathrm{liquid}} = \mathrm{const}$ is pre-defined and the only conditions

$$\Delta G_{A\,\mathrm{melting}} = 0,$$
$$\Delta G_{B\,\mathrm{melting}} = 0 \quad \text{and}$$
$$X_{A\,\mathrm{liquid}} + X_{B\,\mathrm{liquid}} + X_{C\,\mathrm{liquid}} = 1, \tag{6}$$

are satisfied when calculating the equilibrium $X_{A\,\mathrm{liquid}}$, $X_{B\,\mathrm{liquid}}$ and the melting temperature.

According to the previous considerations, an equilibrium composition of the Au–Si–Dy alloy containing 8 at.% Dy was calculated. This alloy composition contains 78.2 at.% of Au and 13.8 at.% of Si and the calculated melting temperature is 294 °C. The vapor pressure of Dy is $<10^{-15}$ Pa at this temperature.

3.2. The Au–Si–Dy LMIS

The current–voltage characteristics of the Au–Si–Dy LMIS is shown in Fig. 3. This form is typical for such kind of sources. The curve has a hysteresis effect around the onset voltage. The threshold voltage is about 3.61 kV and the extinction voltage about 3.56 kV. The reason is that a higher voltage is needed to form than to sustain the Taylor cone. A practically identical dependence is observed for an Au–Si–Pr LMIS [11]. It is worth to note that no significant changes in the electrical parameters of the Au–Si–Dy LMIS took place after 50 h of operation in the FIB system. According to preliminary data, the stability and time of operation of the Au–Si–Dy LMIS are similar to the widely used Au–Si–Be LMIS.

The mass spectrum of the Au–Dy–Si LMIS at a total ion current of 110 pA is presented in Fig. 4. The spectrum is characterized by the presence of lines attributed to emission of Si^{2+}, Si^{+}, Dy^{3+}, Dy^{2+}, Au^{2+}, Au^{+}, Au_3^{2+} and Au_2^{+}. The ion current

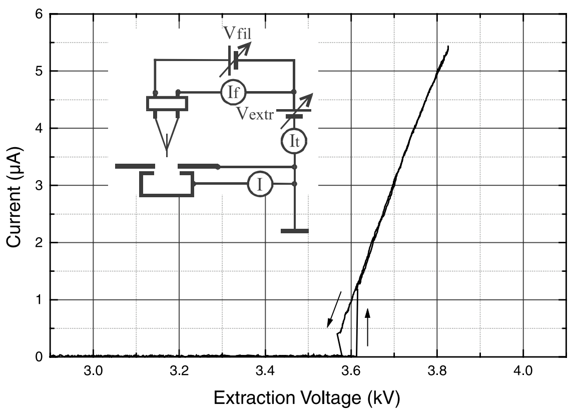

Fig. 3. Current–voltage characteristic of the Au–Dy–Si LMIS. The distance between the emitter tip and the extraction electrode is 2 mm. The heating current is 2.5 A.

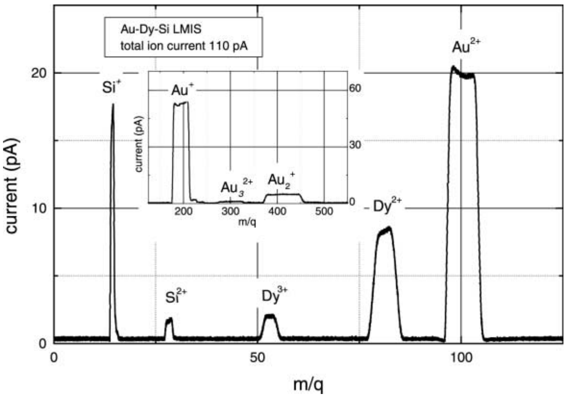

Fig. 4. Mass spectrum of the Au–Dy–Si LMIS at a total ion current of 110 pA and a total source current of 10 μA.

is equal to about 1.6% of the total current for Dy^{3+} and 7.4% for Dy^{2+}, which makes the alloy promising for implantation of Dy ions. It is interesting to note that we observe a substantial Dy^{3+} peak in the mass spectrum, although in an earlier investigation of a Dy–Ni LMIS this peak was not observed. This feature of Au–Si based alloys was found also for an Au–Si–Pr LMIS, where a larger percentage of Pr^{3+} presence was observed in comparison with the pure Pr LMIS [7]. The authors explained this difference by the influence of the Au and Si components on the physical properties of the alloy and thus on the shape of the Taylor cone or on the field strength at the tip of the cone. Apparently, this is a common feature for any alloy and the ratio of differently charged ions in ion beams depends on the components of the selected alloy.

4. Summary

An Au–Dy–Si LMIS for Dy ion FIB implantation was developed. The mass spectrum of the ion beam shows the presence of high intensity Dy^{3+} and Dy^{2+} ions. The fabricated Au–Dy–Si LMIS has high stability and exhibits a long operation time. A simple technique of theoretical calculations for eutectic composition of ternary alloys for LMIS was suggested on the basis of binary phase diagrams of the corresponding elements.

Acknowledgements

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