J. Micromech. Microeng. **10** (2000) 1–6. Printed in the UK PII: S0960-1317(00)99292-1

Electro-discharge machining of mesoscopic parts with electroplated copper and hot-pressed silver tungsten electrodes*

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Received 13 November 1998, in final form 9 September 1999

Abstract. Recent advances in the development of plasma etchers for silicon has brought machines to the market which are able to etch silicon with high etch rates ($>5\ \mu$m min^{-1}) at high anisotropy (taper of sidewalls $<1.5°$). Micromachined silicon is therefore not only suitable for applications in micromechanics but it can also fill the gap which exists between conventional macromachining (milling, turning) with feature sizes usually >1 mm and microelectromechanical systems with feature sizes $<100\ \mu$m.

In this work micromachined silicon is used as a mold for electroplating copper and for hot-pressing silver tungsten. After removing the silicon, the copper or silver-tungsten is used as an electrode for electro-discharge machining. Using these process steps nearly any conductive material can be shaped, in particular magnetic materials like amorphous metal which are difficult or impossible to machine otherwise. The fabrication of the electrodes is described as well as the influence of the electrode material on the achieved quality of the final part.

1. Introduction

Electro-discharge machining (EDM) is a widely used method for shaping conductive materials. EDM removes material by creating controlled sparks between a shaped electrode and an electrically conductive work piece. As part of the material is eroded, the electrode is slowly lowered into the work piece, until the resulting cavity has the inverse shape of the electrode. Dielectric fluid is flushed into the gap between the electrode and work piece to remove small particles created by the process and to avoid excessive oxidation of the part surface and the electrode.

The applications of EDM lie mainly in the tooling industry where it is applied on materials which are too hard to be machined with conventional techniques, such as milling or turning. The parts for these applications are usually larger than 1 mm, therefore conventional methods can be applied for fabricating the electrodes. Due to the fact that EDM can achieve very fine surface finishes, it has been trialed in the micromachining of conductive materials. For this purpose, copper electrodes obtained by LIGA (Lithographie Galvanoformung Abformung) have been used as die-sinking electrodes [1]. A related technique, wire electrodischarge grinding (WEDG), is also capable of fabricating parts with feature sizes below 100 μm [2, 3].

A few alternative methods exist for creating fine patterns in engineering materials. Wire EDM moves a fine wire, which is used as the electrode, through a sheet of part material and moves it along a programmed path. It can reach an excellent surface finish, however it is limited to parts with straight side walls. It cannot create blind holes, and requires highly accurate positioning equipment.

Laser cutting (ablation) has been adapted for micromachining. Instead of electrical sparks, short laser pulses are used to selectively vaporize part material. This method does not require shaped electrodes, but, just like wire EDM, relies upon highly accurate actuators to move the laser over the part surface. The laser pulse rate is substantially lower than the spark pulse rate of micro-EDM machines, which makes the process much slower.

The aim of this work is to show that the application of silicon micromachining in combination with EDM can extend the range of feasible sizes of parts manufactured with shape deposition manufacturing (SDM) [4, 5] by at least one order of magnitude into the mesoscopic range (with part or feature size between 100 μm and 1 mm). For most applications of SDM silicon itself is not a suitable material due to its low fracture toughness and poor electrical and magnetic properties. In order to be able to use engineering materials, silicon therefore serves as a mold for the following processing, in this case as mold for EDM electrodes. The EDM electrodes are then used to shape amorphous metal, a

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* We dedicate this work to one of the pioneers of modern powder metallurgy, Claus G Goetzel, on the occasion of his 85th birthday.

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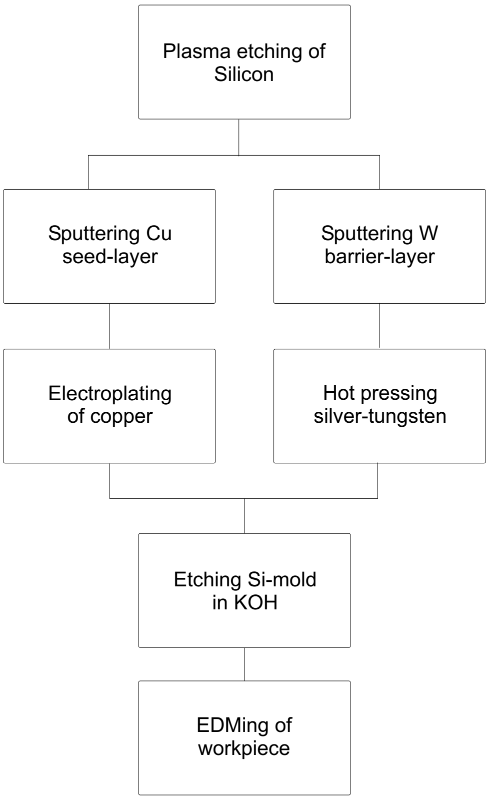

Figure 1. Process steps for the fabrication of plated and hot-pressed electrodes.

soft-magnetic material which is sufficiently conductive to be shaped with EDM. Amorphous metal is delivered in the form of thin sheets (thickness 25 μm) and it is difficult to process with conventional techniques.

Two ways to obtain EDM electrodes for mesoscopic structures are described in the following sections. In figure 1 the process steps necessary to obtain the final part are depicted schematically. By electroplating copper into plasma-etched silicon with sufficient conductivity, one can obtain a copper electrode which replicates the silicon mold. The second way to fabricate mesoscopic electrodes is by hot-pressing of metal powder into the silicon mold. Both alternatives are described.

2. Preparation of silicon molds

To keep the software interface for the fabrication of mesoscopic parts compatible with the computer aided design (CAD) software used in SDM, a software package was developed to slice CAD models and translate the layer information into Caltech interchange format (CIF) format, which is a widely used standard for the description of photolithography masks. Using these photomasks the Si wafer (with thickness between 100 μm and 500 μm, and diameter 100 mm) was patterned with photoresist (7 μm thickness). Highly-doped silicon in the (100) orientation with a resistivity of 0.001 Ω cm was used in order to have a conductivity high enough for the following electroplating. The wafer was then etched in a reactive ion etcher (STS Multiplex ICP Deep RIE) with C_4F_8 as etch gas and SF_6 as passivation gas for the sidewalls. The etch rate was 4 μm min^{-1} and the etch selectivity between resist and silicon better than 80:1. With these etching parameters the taper of the sidewalls was less than 1.5°. After dicing the wafer into square pieces (20 mm by 20 mm), a thin layer of copper was sputtered as seed layer for electroplating (see the next section) and a tungsten layer was sputtered as diffusion barrier onto the wafer pieces which were used for hot-pressing. To promote the adhesion between silicon and copper or tungsten, respectively, the silicon was first coated with a thin (300 nm) titanium layer. In figure 2 a scanning electron micrograph of a plasma-etched silicon mold is shown.

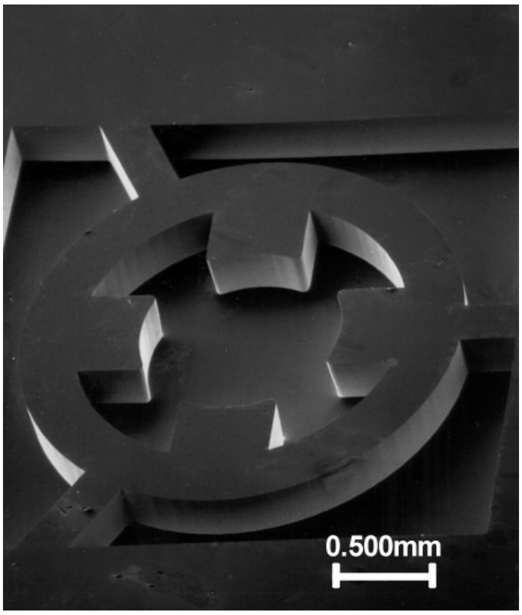

Figure 2. Scanning electron micrograph of plasma-etched silicon mold.

3. Electroplating

Electroplating of microstructures is widely used in combination with optically or x-ray patterned thick resist. In combination with silicon, electroplating has been used to fabricate tools for injection molding and hot embossing [6]. For this work, copper has been plated onto silicon molds in order to fabricate EDM electrodes. Due to its high thermal conductivity, copper is widely used for spark erosion. Furthermore, it is one of the materials which are relatively easy to electroplate.

After sputtering the seed layer onto the plasma-etched silicon mold (figure 2) and removing a residual oxide layer with Metex-9268, these molds were put into an acid copper electroplating solution. A pulse-reverse current source delivered the plating current at a current density of 30 mA cm^{-2}. With these settings a deposition rate of 25 μm h^{-1} was achieved.

After electroplating, the silicon was etched away in an aqueous solution of potassium hydroxide at temperatures between 85 °C and 100 °C. In figure 3 the final electroplated part, obtained from the mold in figure 2, is shown. The height of the structure in figure 3 is 250 μm.

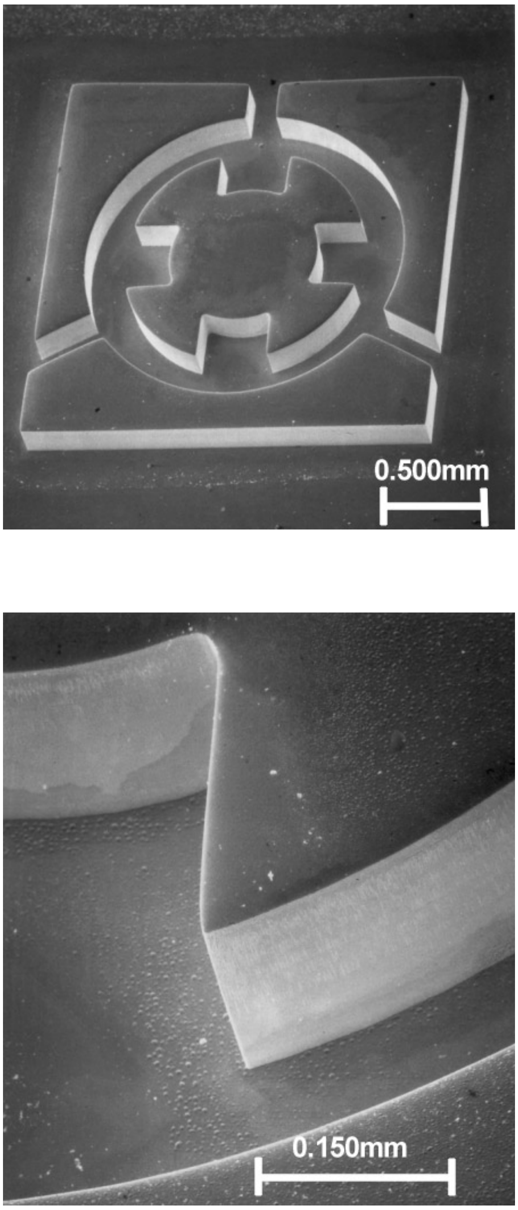

Figure 3. Scanning electron micrographs (full and detailed view) of the electroplated copper electrode.

4. Hot-pressing of metal powder

The ideal materials for EDM electrodes are high melting-point materials such as graphite or tungsten. Both of them cannot be used in combination with silicon because their processing temperature lies above the melting point of silicon, but tungsten in combination with silver or copper has widely been used as contact material in applications such as electrical switches or rocket nozzles. In these materials the high melting point of tungsten is combined with the excellent thermal conductivity of silver and copper. It can therefore be expected to be a suitable material for EDM electrodes. AgW and CuW can either be processed by hot-pressing blended powder or by infiltrating a green tungsten part with liquid silver or copper [7].

When using these materials in combination with a silicon mold, one has to consider the phase diagrams of Si–Ag and Si–Cu, respectively. Silver as well as copper are known to destroy electronic devices by diffusion into the bulk silicon. Recent advances in diffusion barriers [8] allow the use of copper in integrated circuits, but at elevated temperatures in particular ($>$750 °C) [9] these barrier layers tend to fail.

Since copper as well as silver form a low melting eutecticum [10] with silicon (see figure 4), infiltration of the green tungsten part with liquid silver or copper would melt the silicon mold. Therefore, only hot-pressing of blended powder is a viable way to sinter EDM electrodes from metal powders. For two reasons AgW is more suitable for this application than CuW. First, the eutectic temperature of Ag–Si (835 °C) is closer to the melting point of silver (961 °C) than the eutectic temperature of Cu–Si (802 °C) is to the melting point of copper (1084 °C). Hot-pressing of AgW can therefore be done at temperatures significantly closer to the melting point, where silver is already very soft. Second, copper forms various alloys with silicon even at temperatures well below the eutectic temperature (see figure 4). Due to rapid diffusion of copper in silicon, copper tends to form an alloy with the silicon of the mold during sintering and the mold is destroyed. In contrast to copper, silver is nearly insoluble in solid silicon and therefore does not penetrate the mold during hot-pressing.

All hot-pressing experiments were done with a conventional 10 ton hot-press in a graphite die at a temperature of 750 °C and pressures of 30 MPa. The pressing time was 1 h. The powder was made of 33% (weight per cent) tungsten and 67% silver. Prior to pressing the powders were mixed in a steel vessel with steel balls. The viable was agitated in a Spex mill. The particle size of the powders used was between 1 μm and 5 μm. The final density of the AgW part was around 93% of the theoretical full density. The powder replicates the mold sufficiently well, as can be seen from figure 5. The hot-pressing temperature and the applied pressure were low enough to avoid plastic deformation of the silicon, which has been observed at temperatures above 800 °C [11, 12].

5. Electro-discharge machining

The above-described electrodes where used for EDM of commercially available sheets of amorphous metal. Two different alloys (Metglass 2605Co from Allied Signal and Vitrovac 6025 from VAC) were investigated, and both materials yielded similar results. The material was chosen because of its high magnetic permeability and saturation density. It is supposed to be used for the stator of an electromagnetic motor.

For the EDM, a Moldmaster M45-B machine was equipped with a current-reducing head to decrease the spark energy. With an energy of 40 μJ/spark, surfaces as shown in figure 6 are obtained.

The discharge energy of the individual sparks determines the resulting surface finish and also the material removal rate. For rough machining of large tools, discharge pulse energies up to a few joules can be used, whereas finishing operations require discharge energies in the lower millijoule level, with pulse repetition rates of a few kilohertz. With a special adapter head we could reduce the discharge energy

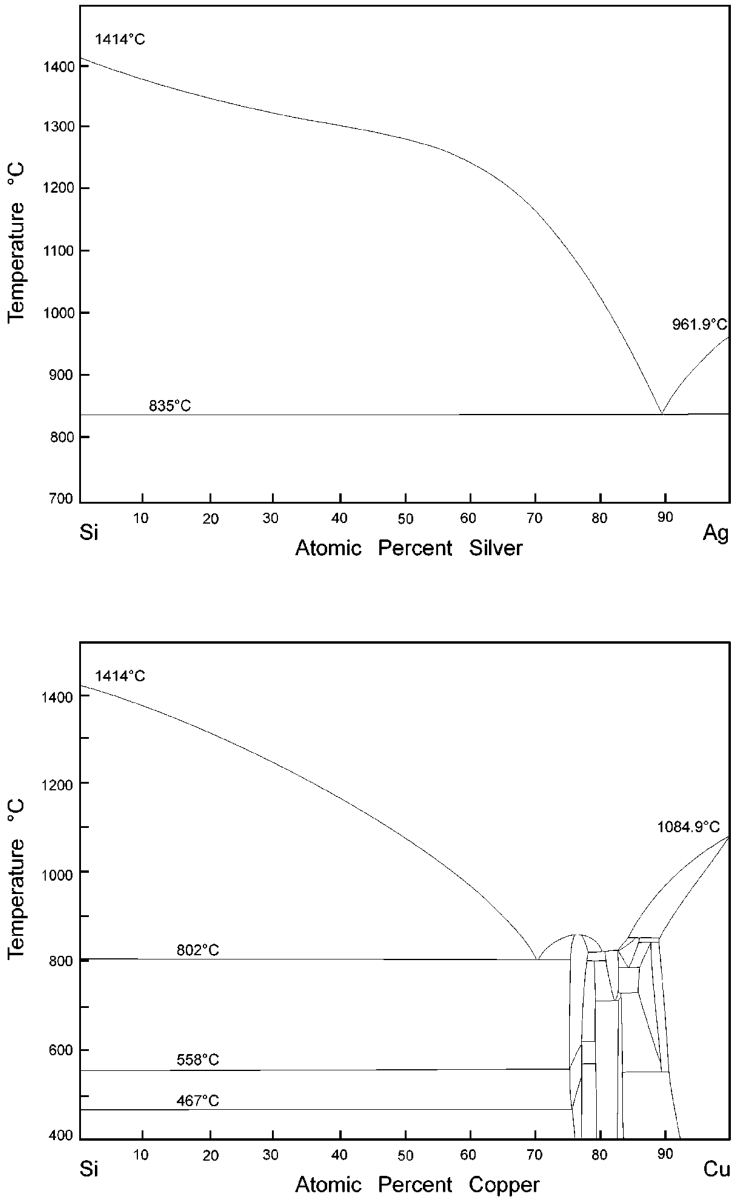

Figure 4. Binary phase diagrams for Si–Ag and Si–Cu from [10].

for our set-up down to 40 μJ. With special micro-EDM controllers the discharge energy per pulse can be reduced below 1 μJ, and much higher pulse repetition rates (several hundred kilohertz) can be reached.

The depth of the remolten material (measured by optical microscopy of the EDM workpiece) is around 3 μm. During the solidification of the remolten zone the amorphous structure of the material becomes lost and is replaced by a thin crystalline layer. The surface finish is (depending on the spark energy and the control settings) between 2 μm and 5 μm. These values can be considered sufficiently low for most applications of mesoscopic devices.

The spark-gap width was found to be 30 ± 3 μm. This value was measured by comparing the dimensions of the original electrode and the final workpiece using optical microscopy. The best tolerances that could be achieved (using the lowest spark energy of 40 μJ/spark) are therefore 3 μm. By using an EDM machine especially dedicated to micro-EDM, even tighter tolerances could be achieved by decreasing the spark energy. By increasing the spark frequency at the same time, machining times could be kept constant.

The tolerances are slightly higher when using AgW electrodes since the inhomogeneous distribution of pores leads to less homogeneous electrode wear. In contrast, the surface finish of the parts eroded with AgW electrodes was smoother than when using Cu electrodes. In figure 6 two sheets of amorphous metal are shown which have been eroded with copper as well as with silver–tungsten electrodes.

6. Conclusions

We have shown two ways to manufacture EDM electrodes for mesoscopic parts. By using silicon micromachining the

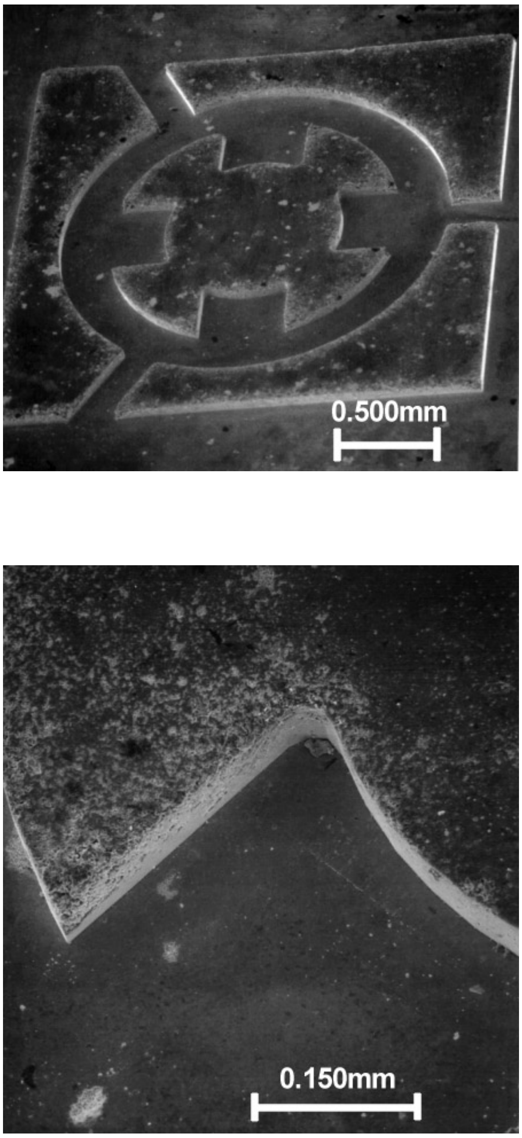

Figure 5. Scanning electron micrographs (full and detailed view) of the hot-pressed AgW electrode.

feasible part size can be reduced by at least one order of magnitude compared to conventional machining techniques. The electrodes are either made by electroplating of copper or by hot-pressing of silver–tungsten powder. Both methods yield electrodes with comparable properties for spark erosion. The electrodes were used to shape amorphous metal, a material which is hard to machine with conventional techniques.

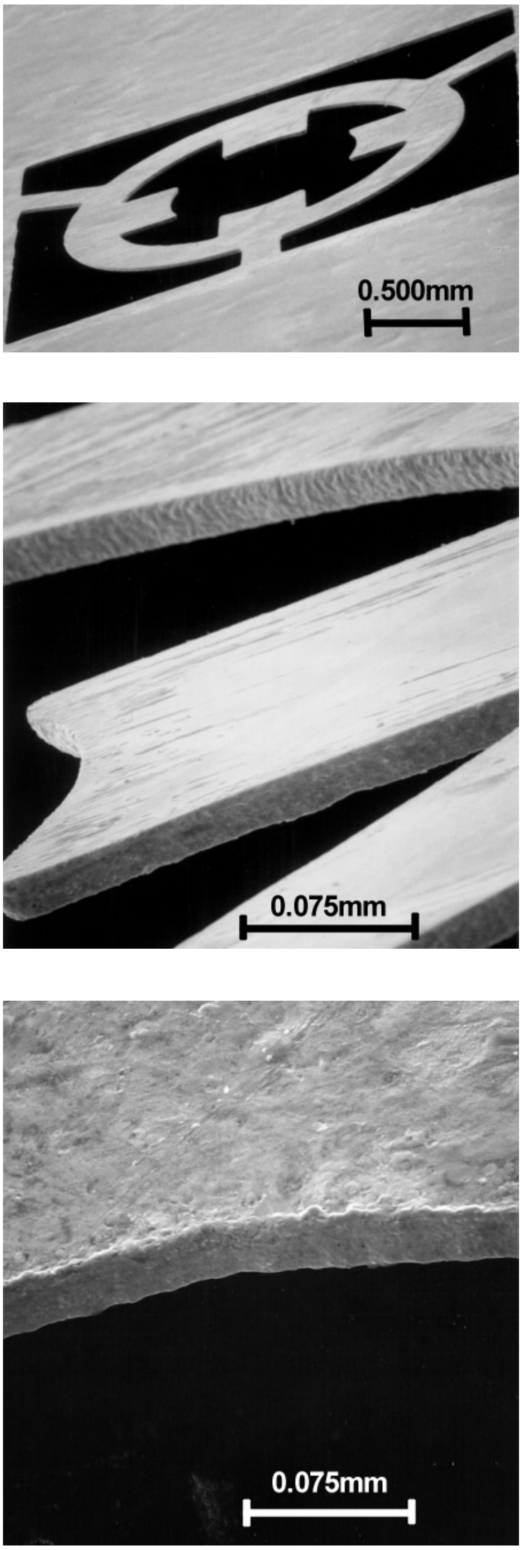

Figure 6. Scanning electron micrographs (full and detailed view) of amorphous metal after EDM with a plated copper electrode (top and middle). The bottom image shows amorphous metal after EDM with an AgW electrode.

Acknowledgments

This work was financially supported by the Defense Advanced Research Projects Agency (DARPA) and the National Science Foundation (NSF). Further financial support came from a Schrödinger fellowship (J1486-TEC) of the Austrian Fonds zur Förderung der Wissenschaftlichen Forschung.

We gratefully acknowledge the advice of Joanna Groza and Jung-Man Doh from UC Davis for the preparation of the metal powders. We wish to acknowledge the technical input and support from Claus Goetzel, Katsuhito Sakamoto and Robert DeMattei of Stanford University as well as from Ali Farvid from SLAC.

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