PLASMA AND ARC MICRODISCHARGES: NEW AVENUES IN MICROFABRICATION

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ABSTRACT

This paper describes the use of microdischarges between lithographically defined features as tools for further processing. Techniques based on the use of microplasmas can facilitate the microfabrication of complex microstructures (with dozens of structural levels) using just two masking steps, whereas micro-arcs can be used to increase the diversity of used in microstructures to WC-Co super-hard metal alloys and other unusual options.

INTRODUCTION

The increasing diversity of applications in microsystems for sensing and actuation motivates a significant amount of research in lithography-based fabrication techniques. The general goals for these processes include the facilitation of structural complexity and material diversity, amongst others. This paper addresses how microdischarges can contribute toward these ends. In particular, it shows how microplasmas can facilitate certain types of structural complexity and micro arcs can facilitate material diversity.

MICROPLASMAS

One aspect of structural complexity is being able to etch materials to a variety of depths (perhaps dozens) in a single microsystem. A conceivable application may be sorting of biological species by size within a microfluidic system. Conventional etchers, however, employ a single plasma that acts over the entire surface area of a wafer. Creating several different etch depths or profiles in a single die mandates the use of a like number of masking steps. In contrast to traditional techniques, an *in-situ* microplasma is formed by applying DC power between two thin-film metal electrodes patterned on the Si substrate and separated by a dielectric spacer (Fig. 1). This arrangement not only shields the substrate from applied electric fields, but also permits the use of DC power, eliminating the tuning requirements of RF plasmas [1]. The tri-layer stack also serves as the hard mask for etching patterns that are smaller than the confinement limit of the microplasma. The stack is fabricated by a two-mask process. Although conventional methods require only one mask, it is notable that when several different etch depths/profiles are required, the microplasma

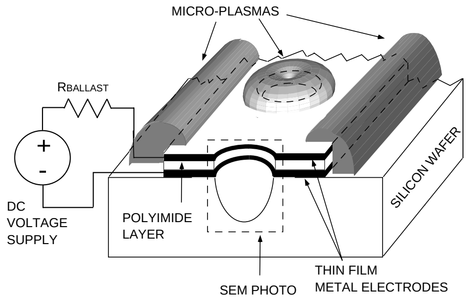

Fig 1: Schematic illustrating the generation of an in-situ microplasma.

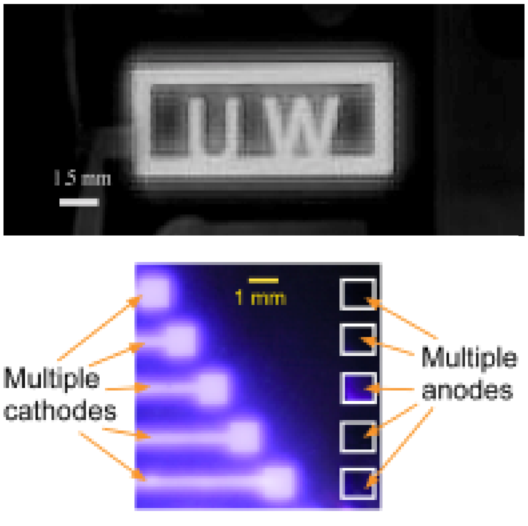

Fig. 2: (a-upper) Local confinement of N_2 microplasmas at 1-20 Torr and -360 V DC in the stacked electrode arrangement; (b-lower) Plasma glow in a planar electrode arrangement.

approach results in net savings because etch parameters of each spatially confined etch region can be individually determined. The relatively small electrode areas for in-situ microplasmas allow power densities in the range of 1-10 W/cm^2 to be achieved at modest levels of input power. The relatively large operating pressures of 1-10 Torr serve to spatially confine the plasmas. It is worth noting that these power densities and operating pressures are orders of magnitude larger than used conventionally.

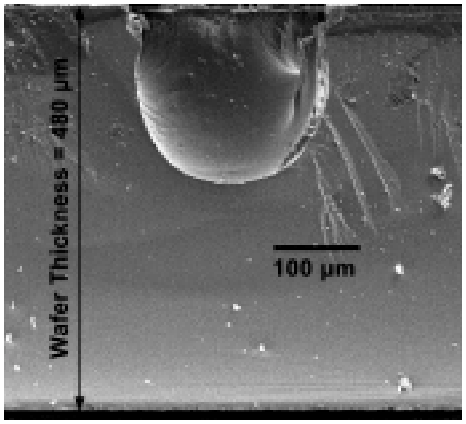

Fig. 3: A 207 µm deep etch using SF_6 (5.2 Torr, 6.8 W/cm^2, 24 min.).

Multiple microplasmas with different etch characteristics may operate sequentially on different regions of a wafer, and simultaneous operation is also possible for many cases. Figure 2a shows the confinement of the plasma around the electrodes of a tri-layer stack. The glow region can be scaled by adjusting the operating pressure and power density. Figure 2b shows the glow region surrounding cathodes that are patterned from the same thin film layer as are the anodes, in an arrangement for which all the electrodes are coplanar. The relative uniformity of the glow region around the cathodes, regardless of the separation from the anodes suggests that the plasma is driven by secondary electrons emitted from the cathodes.

Past work has demonstrated that etch rates >17 µm/min. and through-wafer etches can be achieved using SF_6. A typical etch profile is shown in Fig. 3. The profiles obtained indicate that varying degrees of anisotropy can be achieved using conventional approaches of selecting plasma conditions, gases, and wafer temperature.

MICRO-ELECTRODISCHARGE MACHINING

On the issue of diversity of structural materials, it is often desirable to use certain kinds of metals that are neither conveniently etched by plasmas nor easily deposited by electroplating, chemical vapor deposition, or other methods conventionally used in microfabrication. Micro-electro-discharge machining (micro-EDM) is an attractive alternative that can be used to cut any electrically conductive material, including steel, graphite, silicon, and magnetic materials, including permanent magnets. It involves the sequential discharge of electrical pulses between a microscopic electrode and the workpiece while both are immersed in a dielectric oil [2]. The pulse discharge timing is controlled by a simple RC circuit. The electrode is conventionally a cylindrical metal element which is 5 - 300 µm in diameter. Although it has been commercially used for applications such as ink-jet nozzle fabrication, traditional micro-EDM is limited in throughput because it is a serial process. The use of a single electrode limits not

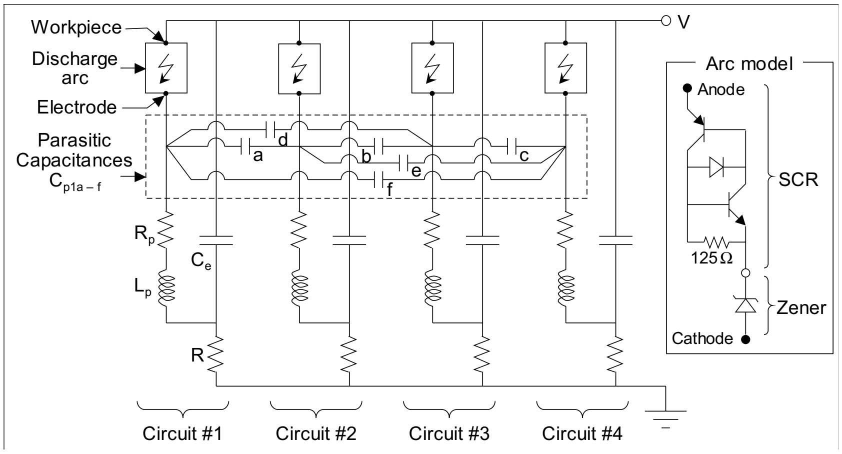

Fig. 4: Four-partition circuit model for SPICE simulation that uses thyristor (SCR) with Zener diode for modeling discharge gap. Each circuit consists of the same element with the same value. L_p, R_p, R, C_e, C_{p1} and V are 1.3 µH, 26 Ω, 1 KΩ, 100 pF, 95 pF and 80 V respectively. Breakdown voltages of thyristor and Zener diode are 50 V and 20 V respectively.

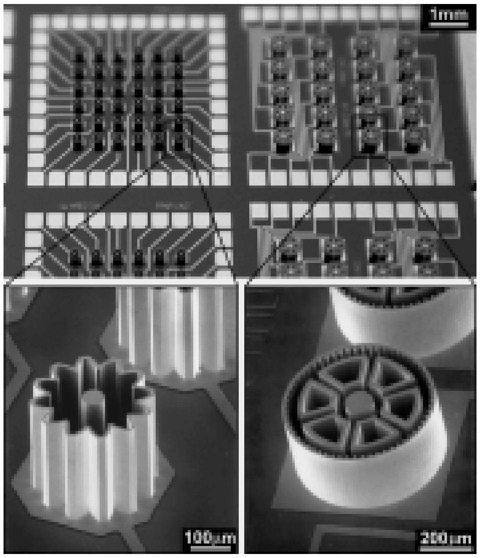

Fig. 5: Cu electrode arrays with patterned interconnect fabricated by using LIGA technique with two-mask alignment sequence.

only the throughput but also precision because the electrodes themselves are individually shaped by using a micro-EDM technique, wire electro-discharge grinding (WEDG) [3], and variation may occur in the electrode shape.

To overcome these throughput and material issues that exist in these technologies, batch mode micro-EDM that uses LIGA-fabricated electrodes has been investigated. The LIGA process uses X-ray lithography to form high aspect ratio molds for electroplated structures [4-7]. In past efforts, it was demonstrated that electroplated Cu electrodes provide acceptable wear resistance [8]. It was also shown a parallel machining for perforations in stainless steel by using 3x4 arrayed electrodes with 100 µm diameter and 500 µm pitch could be achieved.

More recently, we have explored electrode arrays with lithographically fabricated interconnect for the purpose of increasing spatial and temporal density of discharge pulses [9,10]. Examination of machined surfaces and the pulse waveforms reveals that as the number of RC pairs increases, the pulse energy and the surface roughness both increase. These may be attributed to the role of the parasitic capacitance between the patterned interconnect and the Si substrate, which increases the total effective capacitance and also permits cross-talk between electrodes. We have developed an electrical equivalent of the pulsed arc discharge using an SCR and a Zener diode (Fig. 4). This permits the use of SPICE simulation for the discharge circuit to model the impact of electrical parasitics on the cross-talk between partitions in an electrode arrays [11].

A new circuit configuration that uses the on-chip parasitic capacitance instead of external capacitors to control the discharge pulse timing has been developed. The primary changes are that the external capacitors have been dropped and the electrode substrate is tied to the positive supply terminal. This arrangement is highly amenable to large size arrays because all the pulse control circuits elements can be integrated. In addition, it offers accelerated machining rates, and tighter tolerance than conventional schemes. Stainless steel workpieces of 100 µm thickness were machined by 100 µm x 100 µm square cross section electrodes in only 86 s using an 80 V power supply. The machined holes were only 5 µm wider than the electrodes, while the surfaces were smooth and did not exhibit any degradation with increased electrode or circuit multiplicity. These results demonstrate that highly integrated electrodes and circuits will be practical to use for high-yield and high throughput production. Using electrode arrays with four circuits, batch production of 36 WC-Co gears with 300 µm outside diameter and 70 µm thickness in 15 min. was demonstrated (Figs. 5, 6).

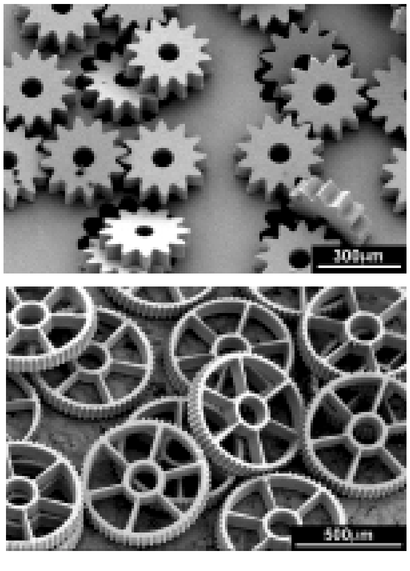

Fig. 6: WC-Co super hard alloy gears cut from a 70 µm thick workpiece using electrode arrays of Fig. 5.

CONCLUSIONS

These efforts demonstrate the use of lithographically fabricated microstructures as process tools that can assist in further fabrication. In the case of microplasmas, patterned thin film metal layers were used as electrodes for a plasma tool which can be used even in the packaging sequence to fine-tune certain elements without the use of lithography at that point. For the case of micro-EDM, lithographically formed electrodes are used to batch process a wide diversity of materials that are not amenable to microfabrication by conventional means.

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REFERENCES

[1] C.G. Wilson and Y.B. Gianchandani, "Silicon micromachining using in situ DC microplasmas," *Journal of Microelectromechanical Systems*, 10(1), March 2001, pp. 50-54

[2] T. Masaki, K. Kawata, and T. Masuzawa, "Micro Electro-Discharge Machining and Its Applications," *Proc., IEEE Intl. Workshop on Micro Electro Mechanical Systems (MEMS '90)*, Napa Valley, California, pp. 21-26, February 1990

[3] T. Masuzawa, M. Fujino, K. Kobayashi, T. Suzuki, and N. Kinoshita, "Wire Electro-Discharge Grinding for Micro-Machining," *Ann. CIRP*, v. 34, pp. 431-434, 1985

[4] W. Ehrfeld, F. Götze, D. Münchmeyer, W. Schelb, and D. Schmidt, "LIGA Process: Sensor Construction Techniques via X-ray Lithography," *Tech. Dig., IEEE Intl. Conf. on Solid-State Sensor and Actuator Workshop (Hilton Head' 88)*, pp. 1-4, June 1988

[5] W. Ehrfeld, H. Lehr, F. Michel, and A. Wolf, "Micro Electro Discharge Machining as a Technology in Micromachining," *Proc., SPIE's Symp. on Micromachining and Microfabrication*, Austin, Texas, v. 2879, pp. 332-337, October, 1996

[6] A. Wolf, W. Ehrfeld, F. Michel, O. Koch, S. Press, H. Soultan, and H.P. Gruber, "Application of New Actuator and Vision Control Systems for Micro Electro Discharge Machining," *Proc., SPIE Conf. on Intelligent Systems in Design and Manufacturing*, Boston, Massachusetts, v. 3517, pp. 149-157, November, 1998

[7] O. Koch, W. Ehrfeld, and F. Michel, "Micro-Electro Discharge Machining - Application, Strategy and Technology," *Proc., 2nd Intl. Workshop on Microfactories (IWMF2000)*, Fribourg, Switzerland, pp. 79-82, October, 2000

[8] K. Takahata, N. Shibaike, and H. Guckel, "A Novel Micro Electro-Discharge Machining Method Using Electrodes Fabricated by the LIGA Process," *Tech. Dig., IEEE Intl. Conf. on Micro Electro Mechanical Systems (MEMS '99)*, Orlando, Florida, pp. 238-243, January, 1999

[9] K. Takahata and Y.B. Gianchandani, "Batch Mode Micro-EDM for High-Density and High-Throughput Micromachining," *Tech. Dig., IEEE Intl. Conf. on Micro Electro Mechanical Systems (MEMS '01)*, Interlaken, Switzerland, pp. 72-75, January, 2001

[10] K. Takahata and Y.B. Gianchandani, "Parallel Discharge with Partitioned Electrode Arrays for Accelerated Batch Mode Micro-EDM," *Tech. Dig., IEEE Intl. Conf. on Solid-State Sensors and Actuators (Transducers '01)*, Munich, Germany, June 2001

[11] K. Takahata and Y.B. Gianchandani, "Batch mode micro-electro-discharge machining," *Journal of Microelectromechanical Systems*, 10(1), Feb. 2002.