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Microfabrication of half-wave rectifier circuits using soft lithography

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Abstract

This paper describes the fabrication of half-wave rectifier circuits using soft lithography. The fabrication process involved two steps of pattern transfer using micromolding in capillaries (MIMIC), and one step using microcontact printing (μCP); two steps required pattern registration. This procedure, with its yield of ~ 90%, demonstrates that soft lithography is compatible with multilayer fabrication, for this type of device. The characteristics at room temperature of the circuits generated using soft lithography were indistinguishable from those fabricated by conventional photolithography.

Keywords: Soft lithography; Rectifier circuits; Microfabrication; MIMIC; μTM

1. Introduction

New methods for the fabrication of micro and nanoscale electronic devices are important for applications in microelectromechanical systems (MEMS), sensors, micrototal analytical systems (μTAS) and other devices in which the cost, performance, design parameters, materials of fabrication, and ease of integration may be weighted differently than in conventional microelectronics, or that may require techniques for fabrication other than photolithography for other reasons. We have begun to develop a new set of fabrication techniques—which we call collectively 'soft lithography'—that address some of these requirements [1]. Soft lithography is a set of replication techniques based on contact printing and polymer molding; it brings useful characteristics for applications requiring low cost, and patterning on large areas and curved surfaces. It is also compatible with a broad range of materials that cannot easily be patterned by photolithography. Soft lithography has been used to fabricate micro and nanoscale features in MEMS [2], microanalytical systems [3], and individual microelectronic components (Schottky diodes [4], thin-film capacitors [5], GaAs/AlGaAs heterostructure field effect transistors [6], and metal-oxide-semiconductor field effect transistors [7]). We are beginning to extend these demonstrations to simple circuits. In the work reported here, we have applied soft lithography to fabricate small arrays of an elementary diode circuit—a half-wave rectifier. The objective of this work is to demonstrate the compatibility of soft lithography with processing technologies used in device fabrication, and to establish its capability in multilayer fabrication.

The fabrication process involved two steps of micromolding in capillaries (MIMIC), one step of microcontact printing (μCP), and required two steps of registration. The diodes in the half-wave rectifier circuits were Schottky diodes fabricated using MIMIC, each comprising one ohmic and one Schottky contact. Both contacts were square pads with dimensions of 160 μm × 160 μm. We used an Al wire, 4.79 mm long and 30 μm wide, fabricated by μCP, as the resistor in the circuit. The resistor was designed with two square contact pads with dimensions of 200 μm × 200 μm. The current–voltage (I–V) characteristics of the Schottky diodes and the resistors were measured separately. We also measured the rectification by these half-wave rectifier circuits and compared the performance of these systems to those fabricated by conventional photolithography.

2. Results and discussion

Fig. 1 illustrates the fabrication procedure for the half-wave rectifier circuits using soft lithography. Fig. 1(a)–(e)

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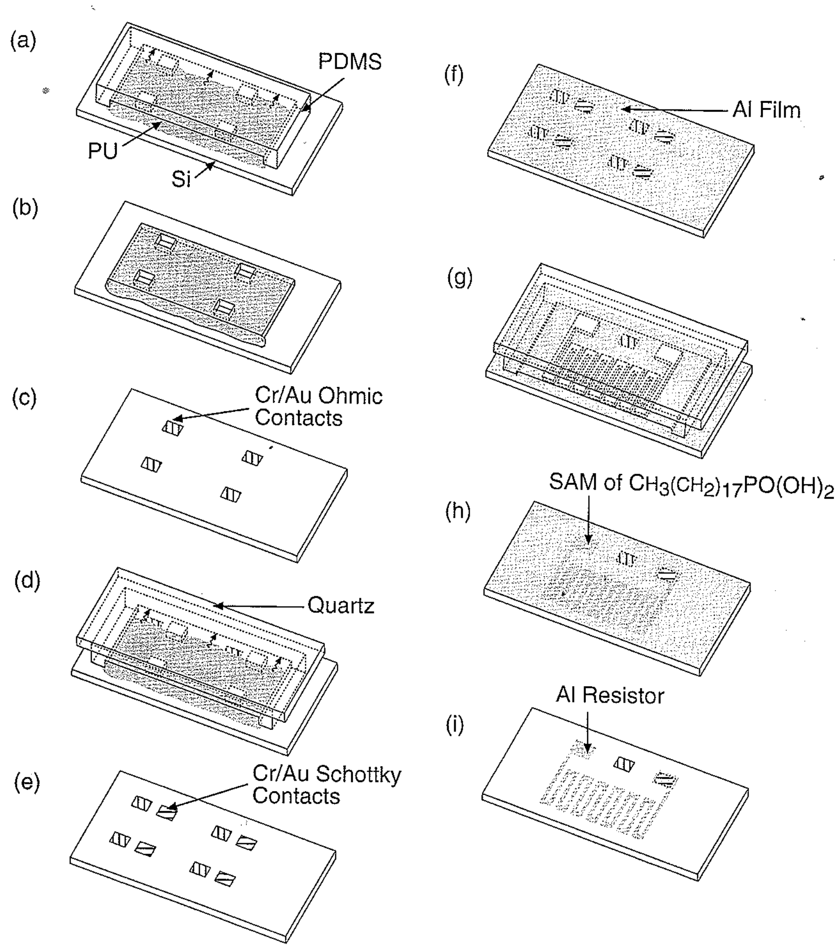

Fig. 1. Schematic diagram of the steps used in fabricating half-wave rectifier circuits using soft lithography. (a) Define ohmic contacts by MIMIC using polyurethane (PU). (b) Cure the PU under ultraviolet (UV), and peel off the PDMS mold. (c) Evaporate Cr/Au, lift off the PU, and anneal to form ohmic contacts. (d) Define Schottky contacts by MIMIC using PU. Use a quartz plate as a support for the PDMS mold to give the required registration. (e) Cure the PU under UV, and peel off the PDMS mold; evaporate Au/Cr, and lift off the PU to obtain Schottky contacts. (f) Evaporate Al to generate a film for μCP. (g) Define Al resistors by μCP using $CH_3(CH_2)_{17}PO(OH)_2$ solution. Use a glass plate as a support to give the required registration. Only the registration of one half-wave rectifier circuit is showed in the diagram. (h) Peel off the PDMS stamp, leaving a self-assembled monolayer (SAM) of $CH_3(CH_2)_{17}PO(OH)_2$ on Al_2O_3. (i) Bake to consolidate the SAM and etch to remove the unprotected part of the Al film and form Al resistors.

outline the procedure for fabricating an array of Schottky diodes: it required two steps of MIMIC and one registration step. There were about 180 Schottky diodes over an area of 1 cm^2. We used rapid prototyping [8] to make the polydimethylsiloxane (PDMS) molds. The roughness of the edge of features fabricated using this technique is about 2 μm; This roughness is set by the printing technique used to draw the patterns [8]. The mold was made by casting PDMS directly on the developed pattern of photoresist and curing at 60°C for 2 h. The relief structure on the PDMS mold used had a depth of 10 μm and the PDMS was about 1 mm thick. In these experiments, the PDMS mold was supported on a quartz plate to facilitate handling, and to limit distortion.

In MIMIC, a PDMS elastomeric mold with interconnected recessed patterns was put in conformal contact with the substrate. Continuous channels were formed between the recessed patterns on the mold and the substrate. A liquid prepolymer was applied to the open ends of the channels and filled the channels by capillarity. The prepolymer was cured under long wavelength UV light, and the mold was then removed. We used a Karl Suss aligner for the registration step. The quartz plate supporting the PDMS mold was mounted on the mask holder, and the sample was placed on the sample holder of the aligner. The position and the orientation of the sample were carefully adjusted before the sample was brought into contact with the mold (Fig. 1(d)).

Fig. 1(f)–(i) describe the fabrication of the second circuit element—the Al resistors—by μCP. In μCP, a PDMS stamp with recessed patterns was 'inked' before it was put in conformal contact with the substrate. The stamp was removed after 10 min; after this time, a SAM had formed on the substrate. The 'ink' used in this step was a 5 mM solution of octadecanephosphonic acid ($CH_3(CH_2)_{17}$-$PO(OH)_2$) in 2-propanol [9]. The substrate was the sample with the Schottky diode arrays covered with a thermally evaporated Al film. The registration step here was analo-

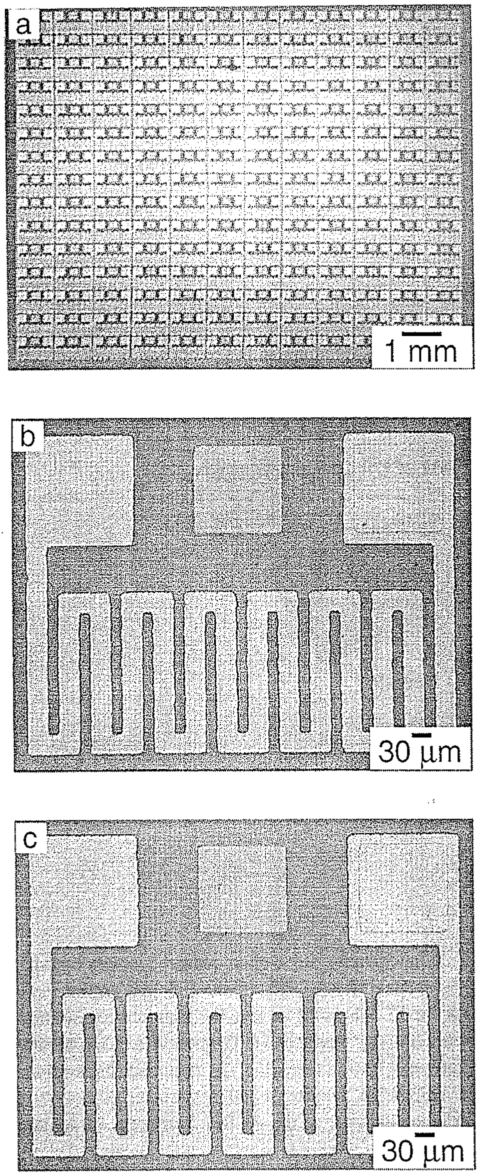

Fig. 2. Optical micrographs of half-wave rectifier circuits fabricated by soft lithography. (a) The entire array of the half-wave rectifier circuits. (b) A magnified view of one circuit from the center of the array. (c) A magnified view of one circuit from the edge of the array.

gous to that used in the fabrication of Schottky diodes, except that we inked the PDMS stamp before placing it on the glass plate.

The procedure used for µCP was more demanding than that for MIMIC. During the registration of the PDMS mold and the sample in MIMIC, we could separate the mold and the sample even after they were in local contact. In µCP, however, the sample would be printed as soon as it was contacted by PDMS stamp, so it was essential to adjust the position and the orientation of the sample before it contacted the stamp. Sagging of the PDMS stamp was also an important issue, and its control required appropriate design [10]. Sagging can cause the transfer of $CH_3(CH_2)_{17}$-$PO(OH)_2$ into undesired areas during µCP. The depth of the relief structure in the PDMS stamp played an important role in controlling the sagging and deformation of the PDMS stamp [10]. If the depth was too small, sagging was important; if the depth was too large, lateral deformations would occur. Considering both issues, we chose the depth of the relief structure in the PDMS stamp to be 4.5 µm. The PDMS stamp was about 1 mm thick, the same as in MIMIC. After registration and removing the PDMS stamp, we baked the sample to consolidate the SAM. Wet etching removed the unprotected part of the Al film and formed the Al resistors. The etching solution contained phosphoric, acetic, nitric acids and water in a ratio of 16:1:1:2 (this ratio is from Ref. [11]).

Fig. 2 shows the images of half-wave rectifier circuits fabricated by these soft lithography processes. Fig. 2a is an optical micrograph of the entire array of half-wave rectifier circuits. A typical sample was patterned over a 1-cm^2 area and consisted of approximately 180 half-wave rectifier circuits. Fig. 2b is a magnified view of one half-wave rectifier circuit from the center of the array. Fig. 2c is a magnified view of one half-wave rectifier circuit from the edge of the array. To evaluate the registration, we defined the error in the registration as the difference between the relative positions of the Al resistor and the Cr/Au ohmic contact in different circuits. The error was less than 20 µm over a 1-cm^2 area. The factors that seemed most to affect registration were the sagging and variation in the thickness of the PDMS mold or stamp. If one side of PDMS mold or

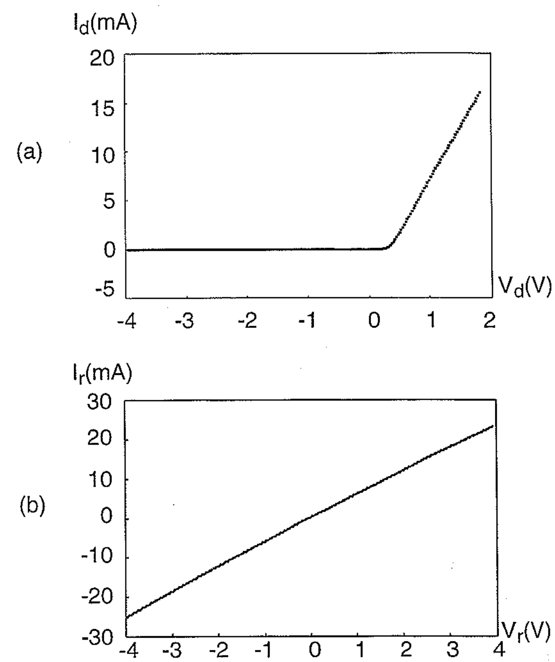

Fig. 3. Performance of Schottky diodes and Al resistors in the half-wave rectifier circuits. (a) The $I-V$ characteristics of a typical Schottky diode. The X-axis is the DC voltage applied on the diode (V_d). The Y-axis is the diode current (I_d). (b) The $I-V$ characteristics of a typical Al resistor. The X-axis is the DC voltage applied on the resistor (V_r). The Y-axis is the resistor current (I_r).

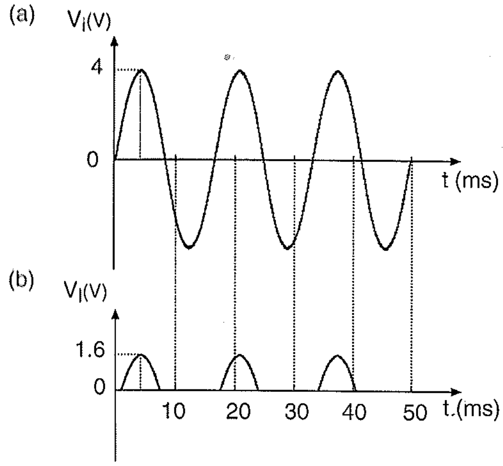

Fig. 4. Performance of a representative half-wave rectifier circuit fabricated by soft lithography. (a) The input voltage. The frequency was 60 Hz. (b) The output DC voltage achieved by rectification in the circuit.

stamp was significantly thicker than the other, local sagging occurred and the error in the registration increased.

The edge roughness was ~ 2 μm; this value was mainly determined by the masks used in the rapid prototyping process. Wet chemical etching could also, in principle, contribute to the edge roughness of the Al resistors. To study the contribution of the wet chemical etching to the edge roughness, we used a Cr mask that had a edge roughness less than 50 nm to make a PDMS stamp. The edge roughness of the Al structures obtained in tests with this stamp after wet chemical etching was about 150 nm; we can thus attribute $\sim$ 100–200 nm of the edge roughness of the Al resistor to wet chemical etching. This contribution was not significant for the Schottky diodes and Al resistors, both of which had edge roughness of about 2 μm. The pattern transfer yield was defined as the ratio of the patterns successfully transferred onto the sample to the patterns designed in the masks. The yields in both MIMIC and μCP steps were $> 98\%$.

Fig. 3 shows the measured direct current performance of a representative Schottky diode and an Al resistor. In Fig. 3(a) the current–voltage (I–V) characteristics of the Schottky diode were indistinguishable from the I–V characteristics of a Schottky diode fabricated by photolithography [4]. The forward break voltage of the diode was $V_F \approx 0.35$ V and the reverse current before diode breakdown was in the microampere range. Fig. 3(b) is the I–V characteristics of the Al resistor. The resistivity of the Al resistor was $\rho \approx 5.7 \times 10^{-8}$ Ω m, the same as the resistivity of the Al resistor fabricated using photolithography.

Fig. 4 shows the alternating current performance of a representative half-wave rectifier circuit. The input voltage V_i was sinusoidal: that is, $V_i = V_{im} \sin(2\pi f t)$. The frequency, f, was 60 Hz and $V_{im} = 4$ V. The nonlinear nature of the diode response distorted the output waveform (i.e., caused it to have a shape different from V_i). The output voltage had a maximum of 1.6 V, close to the theoretical performance for this circuit (the maximum of the output voltage is about 1.55 V by graphical analysis) [12]. The performance of these circuits was similar to those fabricated by conventional methods [13]. The final yield of functional half-wave rectifier circuits was $\sim 90\%$. This yield was evaluated by calculating the ratio of the number of functional circuits in the final samples to the number of the circuits in the designed masks. The defects that caused failures were poor ohmic contacts, and errors in pattern transfer due to distortions in the PDMS stamp.

3. Conclusions

Using the fabrication of half-wave rectifier circuits as a model system, we have demonstrated the ability of soft lithography to fabricate a simple microelectronic circuit in a process requiring two registration steps with feature sizes of ~ 30 μm. About 180 half-wave rectifier circuits were fabricated over a 1-cm^2 area with a yield of about 90%. The smallest feature size in the half-wave rectifier circuits fabricated here was 30 μm, a limit set by the masks we used. Smaller dimensions are, however, achievable with higher resolution masks [1]. The error in the registration in this multilayer fabrication process was less than 20 μm over a 1-cm^2 area. If we can reduce the distortion of the PDMS mold or stamp used in the registration further, by, for example, casting the PDMS directly against a rigid support, we believe we can reach small errors in registration of < 1 μm [14].

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