Sacrificial Layer Process with Laser-Driven Release for Batch Assembly Operations

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***Abstract*—A dry sacrificial layer process is presented in which microstructures fabricated on UV-transparent substrates are released by excimer laser ablation of a polymer sacrificial material using laser light incident from the reverse side of the substrate. We investigate the application of this technique to the batch assembly of hybrid microelectromechanical systems (MEMS) built from parts fabricated on different substrates. Preliminary measurements of initial velocity are presented for nickel test structures released from polyimide sacrificial layers using a KrF excimer laser. At fluences in the range 50–250 mJ/cm^2 (i.e., close to the ablation threshold), structures with heights of 100 μm are shown to exhibit initial velocities in the range 1–5 ms^{-1}, allowing controlled transfer of parts between substrates. Application of the new assembly method to a MEMS device is demonstrated by assembling arrays of electrostatic wobble motors from component parts fabricated on separate substrates by UV-LIGA processing. [320]**

***Index Terms*—Batch assembly, excimer laser ablation, impulse coupling, sacrificial layer process.**

I. Introduction

MICROELECTROMECHANICAL systems (MEMS) technology is set to enjoy massive growth over the coming decade. Batch fabrication methods based on very large-scale integration (VLSI) processing have the potential for low-cost manufacture, tight process control, and improved reliability through increased integration. Several key fabrication methods have emerged to date, notably bulk silicon micromachining [1], surface silicon micromachining [2], [3], newer processes which combine these [4], and the LIGA process [5]–[7]; these processes, together with other emerging technologies, represent a microengineering "tool kit" which is capable of producing an enormous range of sensor and actuator devices, and attention has already been turned to more complex systems which also contain electronic and/or optical signal routing and processing [8]. One of the central aims of MEMS research in the future will be to develop fully integrated fabrication processes for such systems. This is a major challenge since the fabrication sequences and material requirements of different subsystems are, in many cases, conflicting. Unsurprisingly, progress to date in this area has been confined largely to the integration of silicon-micromachined components with CMOS circuitry [9], [10].

While fully integrated fabrication processes must remain a long-term goal, hybrid approaches will also be important, particularly in the medium term. This has clearly been recognized in certain areas of microtechnology. For example, a considerable amount of effort has been invested in hybrid optical circuits, where different component parts (e.g., lasers, photodetectors, and modulators) are made by established fabrication routes and then hybridized on a silicon motherboard [11]. The development of wafer-scale assembly techniques for hybrids of this type could eliminate the bottleneck associated with current pick-and-place methods.

Microassembly has received relatively little attention in the past, primarily because the emphasis in most MEMS research has been on the fabrication of relatively simple integrated devices. In cases where assembly has been required, the numbers of components involved have been small enough for manual assembly under a microscope to be feasible. Nevertheless, there is an increasing awareness of the need for more advanced assembly methods, and a number of novel techniques have emerged in recent years. One notable example is the use of fluid transport to assemble arrays of laser diodes on silicon [12]. Machine-assisted assembly of individual devices has also been investigated [13], [14], although this approach, like manual assembly, does not enjoy the benefits of batch processing.

Even in situations where the component parts of a device or system can be fabricated monolithically, there may be some advantage in being able to rearrange those parts. For example, three-dimensional (3-D) structures can be produced by reconfiguring components made by planar VLSI processing. This approach has been used previously to create an optical microbench on silicon. Components were formed on flaps by sacrificial layer processing, and subsequently rotated out of plane [15], either manually or using electrostatic actuation. Automatic rotation of silicon and metal flaps using surface tension forces has also been demonstrated [16], [17]. Several other methods have been proposed for reconfiguring monolithically integrated components, including the use of resistive heating to weld together or separate polysilicon structures [18], and the use of built-in stress to deflect cantilevers [19].

In this paper, we present a novel technique for wafer-scale assembly of hybrid devices. The method is applicable to devices which can be z-axis assembled (i.e., assembled by adding components from one direction only) and for which the component parts may be fabricated on, or transferred to,

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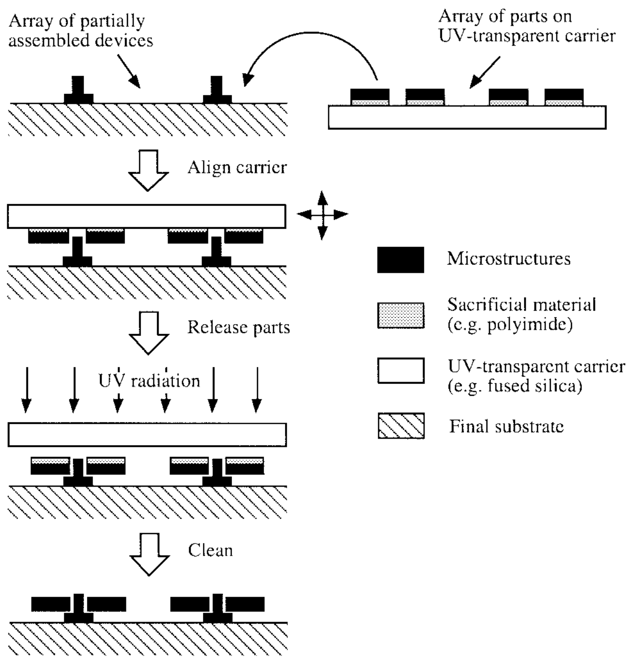

Fig. 1. Basic laser-assisted assembly process.

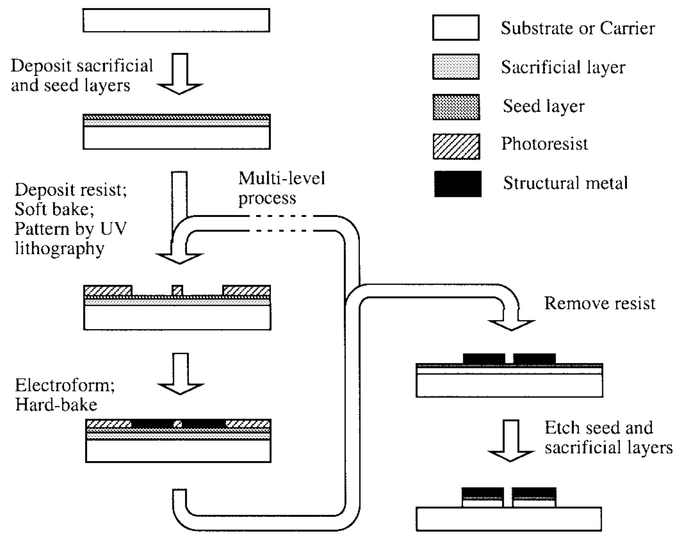

Fig. 2. Sacrificial UV-LIGA process.

UV-transparent carriers with intermediate polymer sacrificial layers. Assembly is achieved by aligning each carrier in turn over an array of partially assembled devices and then illuminating the carrier from above with an intense pulse of UV radiation from an excimer laser, as shown in Fig. 1. Laser exposure causes a thin layer of polymer on the upper side of the sacrificial layer to vaporize by ablation [20], releasing the components.

A postassembly cleaning step is required to remove ablation debris from the final substrate and also any residual sacrificial material on the upper surfaces of the released components. Conventional oxygen plasma ashing may be used here, provided the assembled devices can withstand vacuum processing and are resistant to attack by the O_2 plasma. Other steps such as bonding, which are beyond the scope of this paper, will also be required in general.

In situations where the components to be added are not on the same grid as the devices, individual components can be released by exposing the carrier through a mask. Serial assembly can then proceed by moving each device/component pair in turn into position beneath the mask opening and exposing. Even in this case, only one initial alignment step should be required provided the translation stages can position subsequent device/component pairs with sufficient accuracy by dead reckoning. Note that the mask used for selective release, or at least the CAD data which defines it, can be identical to that used in fabrication of the component. This mask can either be placed immediately over the carrier, or imaged onto the sacrificial layer using suitable projection optics [21]. In general, the latter option is preferable as propagation through the carrier does not lead to any loss of resolution by diffraction.

The proposed assembly method is strongly compatible with LIGA-derived fabrication processes since these allow the production of component parts directly on UV-transparent carriers with polymer sacrificial layers. This is true of all three major variants of LIGA, i.e., those in which the primary resist structures are formed by conventional UV lithography [22]–[25], deep plasma etching [26], [27], and excimer laser micromachining [28], [29]. In fact, other workers have previously demonstrated the fabrication of nickel structures on glass wafers with photoresist sacrificial layers by the UV lithography method [30], although wet chemical release was used in this case. Conventional X-ray LIGA can also produce metal structures on polymer sacrificial layers, although poor adhesion of the X-ray resist (usually cross-linked polymethylmethacrylate) can be a problem.

The remainder of this paper is organized as follows: in Section II, we describe a sacrificial UV-LIGA process for fabricating laser-releasable components. Sections III and IV, respectively, cover basic laser release experiments—aimed at establishing typical initial velocities for laser-released microstructures—and batch assembly demonstrations. Conclusions and suggestions for future work are contained in Section V.

II. Fabrication of Component Parts

All test structures used in this work were fabricated by the process shown in Fig. 2. Starting with a 3-in-diameter 1.5-mm-thick fused silica wafer, a polymer sacrificial layer is deposited by spincoating, followed by a metal electroplating seed layer. Metal structures are then formed by UV lithography and electroforming, which may be repeated if necessary to produce multilevel structures. The process as shown cannot produce multilevel structures with overhanging features because there is no interlevel seed layer deposition step. However, such a step can be introduced if required [31]. Following the final electroforming step, the resist is removed and the exposed regions of the seed and sacrificial layers are etched away.

Two sacrificial layer materials were investigated: polyimide (Du Pont Pyralin, type PI2540) and optical photoresist (Shipley S1813). However, it was found in initial experiments that deep (>50 μm) metal structures had a tendency to separate from photoresist sacrificial layers at the resist removal stage, probably as a result of penetration of the seed layer by the resist stripper, either through pin holes or defects arising from the electroforming process. This problem did not arise with polyimide, and, consequently, polyimide was used in all later experiments. A thickness of 3 μm was used in most cases; this was well above the ablation depth per laser pulse (<0.1 μm at 100 mJ/cm^2 fluence), but thin enough to be removed easily by plasma etching after release. The polyimide was partially imidized after spincoating by baking at 200°C in air.

Three types of photoresist were used according to the layer thickness required: Shipley S1813 (up to 2 μm), Hoechst AZ4562 (5–20 μm), and Morton LM5000 dry film resist (above 20 μm). In all cases, the electroformed metal was nickel and the seed material was copper (2000 Å thick, evaporated or sputtered). Resist removal was performed using either acetone (for S1813 and AZ4562) or a commercial alkaline stripper (for LM5000); the exposed seed layer was removed using ISOFORM aluminum etch (a good selective etch for copper in the presence of nickel), and the exposed sacrificial material was stripped by reactive ion etching (RIE) (see Section IV).

III. Laser-Driven Release Experiments

Preliminary experiments were performed to establish typical values for the initial velocities of microstructures released from polymer sacrificial layers. Laser-driven release is essentially an explosive process in which the material ablated from the sacrificial layer expands and cools, imparting a mechanical impulse to the carrier and the released part. This so-called impulse-coupling phenomenon has been studied extensively in the past by other workers, both experimentally and on a theoretical basis (see, for example, [32] and [33]), and two important regimes have been identified: "normal ablation," where the ablative target is in a vacuum or a gaseous ambient, and "confined ablation," where the target is covered by a transparent overlay [34]–[36]. The latter closely resembles the situation arising in laser-driven release.

Measurements of initial velocity were made for nickel structures released from silica carriers with polyimide sacrificial layers, using the apparatus shown in Fig. 3. Individual structures were released into a vertical tube by exposure to single pulses from a KrF excimer laser (Lumonics, type TE-861M-4) and their times of flight over a distance of 7 cm were measured using a search coil; the values obtained were converted to initial velocities, with correction for gravitational acceleration. The structures used were 2 × 2-mm square pads with heights of 50–200 μm. The laser fluence was adjusted by moving the focusing lens and/or inserting an attenuator and measured on a pulse-by-pulse basis using a monitor photodiode; the latter was calibrated prior to the experiment against an energy meter placed after the final aperture. The tube was evacuated to 10 mbar to reduce the effects of air resistance.

Fig. 4 shows the measured variation of initial velocity with laser fluence for structures with heights of 100 μm. The initial velocity rises relatively steeply with fluence above the ablation threshold, tending to level out at higher fluences. This is broadly consistent with a simple model based on energy and momentum conservation, which was used by Fabbro *et al.* in [35]. Assuming some fraction η of the available laser energy is converted to kinetic energy of the released component and the carrier, then we have

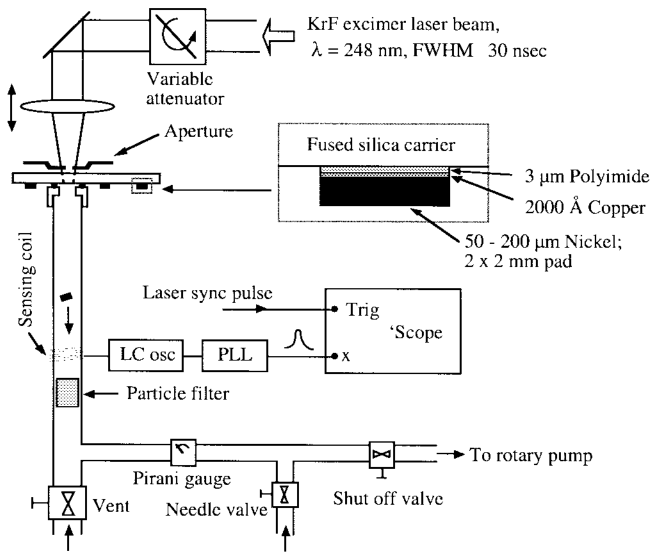

Fig. 3. Experimental setup for initial velocity measurements.

$$2\eta(E - E_T) = m_1 V_1^2 + m_2 V_2^2, \qquad E > E_T \tag{1}$$

$$m_1 V_1 = m_2 V_2 = J \tag{2}$$

where m_1 and m_2 are the masses (per unit area) of the released component and carrier, respectively, V_1 and V_2 are the corresponding velocities of separation, J is the mechanical impulse imparted, and E is the laser fluence. In (1), we are assuming that only the excess fluence above the ablation threshold E_T can contribute to impulse coupling; this is consistent with thermal coupling measurements [37] which indicate that the thermal load on a polyimide target remains roughly constant above the ablation threshold. The initial velocity of the released component is then given by

$$V_1 \approx [2\eta(E - E_T)/m_1]^{1/2} \tag{3}$$

where we have assumed $m_1 \ll m_2$. The solid line in Fig. 4 is the variation of V_1 predicted by (3), assuming $E_T \approx 35$ mJ/cm^2 (after [37]) and with $\eta = 0.42\%$.

While (3) is reasonably consistent with experimental observations, it should be viewed with some caution since there is no reason to suppose that the energy conversion efficiency η will be constant over a wide range of fluences. Acceleration of the released part competes with numerous other processes, including heating of the released part and carrier, heat of vaporization, and lateral expansion of the ablation products [35]; the effects of these processes on the impulse coupling efficiency at fluences close to the ablation threshold are not yet known in detail. All we can say with certainty is that the kinetic energy of the released part accounts for only a tiny fraction of the incident laser energy, most of which is lost to other processes.

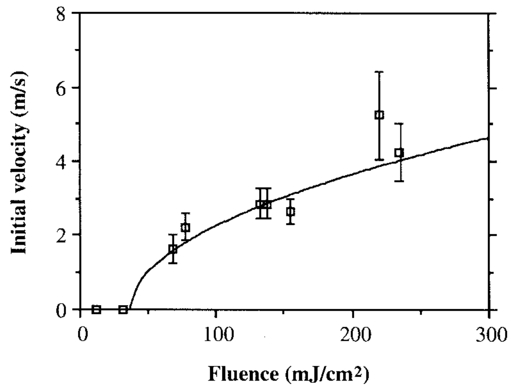

Fig. 4. Measured variation of initial velocity with laser fluence at 248-nm wavelength for 100-μm-high nickel structures released from 3-μm-thick polyimide sacrificial layers. Solid line is (3) with $E_T = 35$ mJ/cm^2, $\eta = 0.42\%$.

From the initial velocities in Fig. 4, we may also conclude that, in the absence of air resistance and for the fluence range shown, gravitational acceleration will have a negligible effect on the transit time of the released component between carrier and substrate. We can tentatively extend the results to thinner components by assuming that the conversion efficiency η depends only on fluence. In this case, the initial velocity should be inversely proportional to the square root of the component height h. Thus, at $E = 100$ mJ/cm^2, we would expect the initial velocity to vary from around 2 ms^{-1} at $h = 100$ μm to 20 ms^{-1} at $h = 1$ μm, corresponding to transit times over a 100-μm gap of between 5 and 50 μs. These values are small compared to the equivalent transit time under freefall from rest, which is 4.5 ms.

A key question from the point of view of the overall viability of the process is whether the kinetic energy generated on laser release can be dissipated without damage being incurred by the released component and/or the final substrate through plastic deformation. Assuming the component strikes the final substrate with velocity V_1 and all of its kinetic energy is converted to compressive strain within the component itself, then the resulting local strain will be at least of order $\varepsilon = V_1(\rho/Y)^{\frac{1}{2}}$, where ρ and Y are the density and Young's modulus of the component, respectively. For a nickel structure ($\rho = 8.9 \times 10^3$ kgm^{-3}, $Y \approx 200$ GPa) with $V_1 = 2$ ms^{-1}, this yields $\varepsilon \approx 0.04\%$, which is not far below the elastic limit. This suggests that in developing the process we should look for ways to reduce the initial velocities from their current values.

One important factor we have neglected in the previous discussion is air resistance. In practical assembly situations, where components are transferred between two wafers in close proximity, squeeze-film effects may provide a mechanism for absorbing a significant fraction of the kinetic energy. We have yet to investigate this aspect in detail.

IV. Batch Assembly Demonstrations

Assembly experiments were carried out using a purpose-built alignment and exposure rig, which is shown schematically in Fig. 5. The carrier (upper wafer) and the final substrate (lower wafer) are held on annular vacuum chucks and viewed from beneath by a microscope attached to a CCD camera. The wafers are aligned by means of manual X, Y, and Θz micropositioners and then brought into proximity by inflating a bellows between the upper chuck and the outer frame, with spacers being used to establish a well-defined proximity gap. This arrangement can routinely achieve alignment accuracies of 3–5 μm. The entire rig is mounted on a motorized X–Y stage, allowing step-and-repeat assembly operations under control of a personal computer.

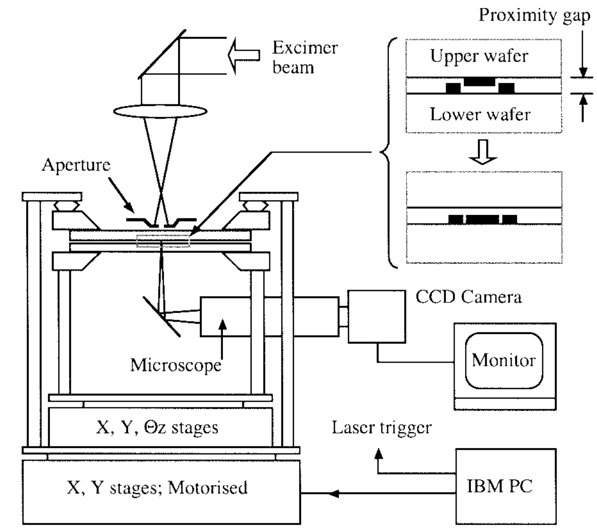

Fig. 5. Experimental setup for laser-assisted assembly experiments.

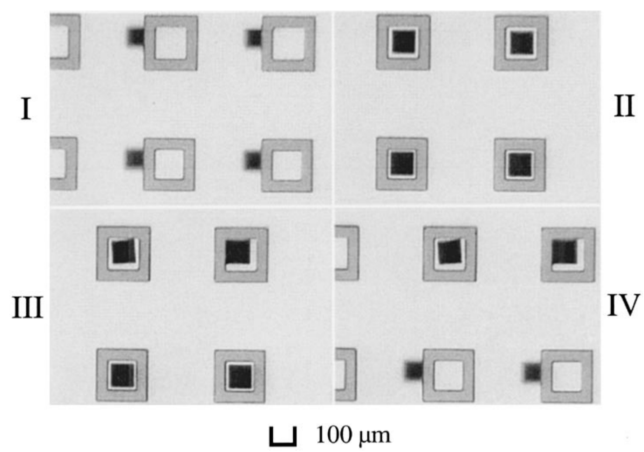

Fig. 6. Demonstration of laser-assisted assembly using nickel pads and frames showing CCD camera images of a 4 × 4 array (100-μm pads) at various stages of assembly: I) Prealigned—wafers at large separation with all four pads on upper wafer. II) Aligned—wafers in proximity and ready for exposure. III) Exposed—two pads now on lower. IV) Separated—upper wafer moved away.

For an initial batch assembly demonstration, pairs of silica wafers were prepared with arrays of square pads on one wafer and complementary "frames" on the other, i.e., larger pads with square cutouts. The pads had side lengths in the range 10–500 μm, and the pad-frame clearance was varied from 2 to 25 μm; all structures were 15 μm high. Fig. 6 shows the CCD camera image for an array of four 100-μm pads at various stages of the assembly process.

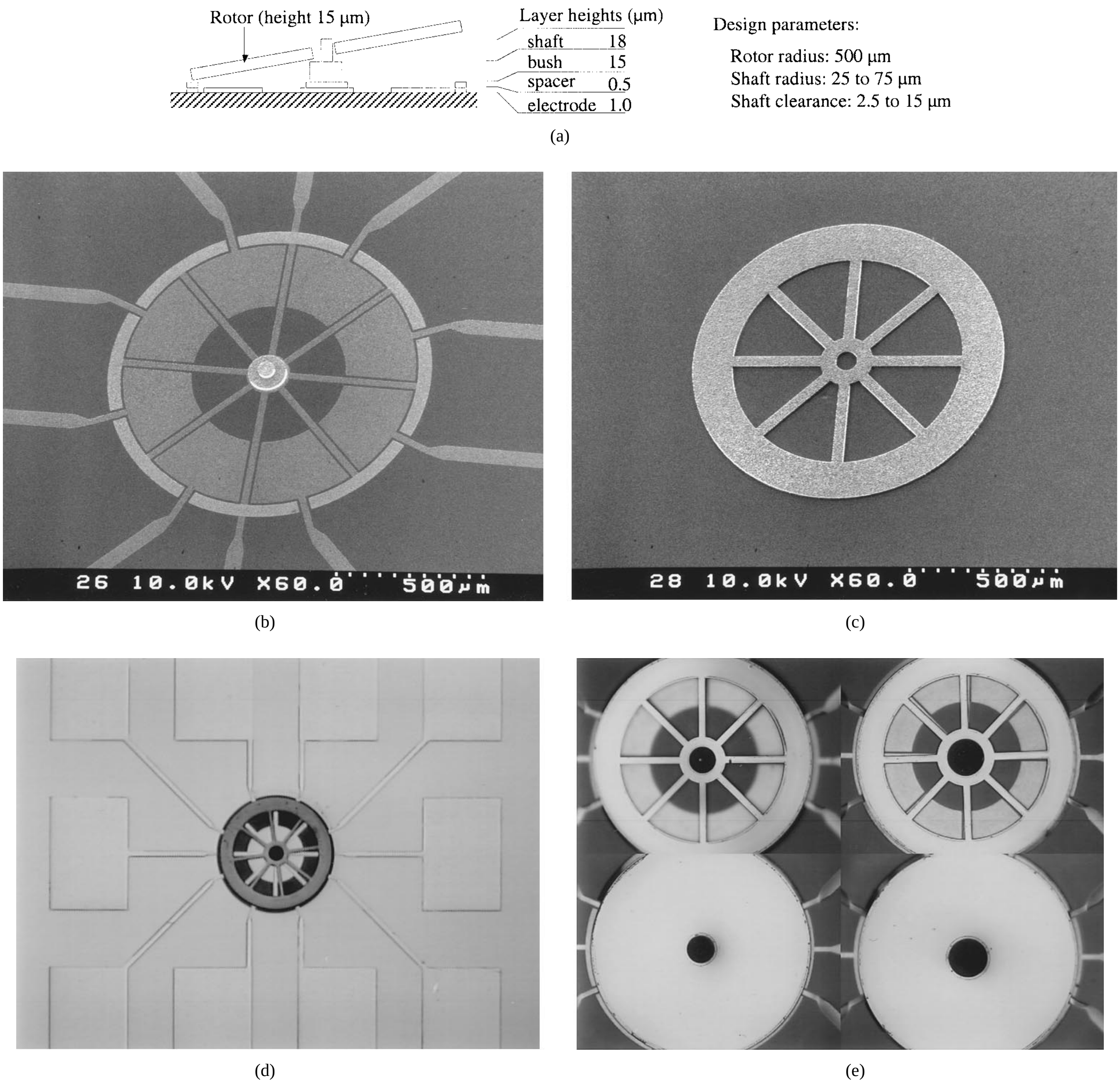

Fig. 7. Laser-assembled wobble motor. (a) Structure and design parameters. (b) and (c) SEM images of stator and rotor prior to assembly. (d) Single laser-assembled device. (e) Four devices of different designs from an array of 16 laser-assembled by step-and-repeat with a single alignment operation.

From images III and IV, it is clear that the released structures have “walked” laterally and, in one case, also rotated during release. In fact, it was found generally that reliable transfer of pads into their associated frames occurred only when the proximity gap between the two wafers was less than the combined nickel height, with large and apparently random lateral displacements occurring at higher separations. This suggests that the inherent placement accuracy of laser release—that is, the placement accuracy in the absence of structural features to guide trajectory—may be limited. This aspect requires further investigation. In particular, the influences of fluence level, beam homogeneity, and ambient gas pressure are not yet known.

The structures shown in Fig. 6 form part of a larger array in which selected pads were released in step-and-repeat mode by exposing through a 500-μm-diameter aperture. By removing the aperture, parallel release of groups of up to 50 structures was also demonstrated. The principle extends immediately to larger arrays, the maximum array size being limited by the laser pulse energy. For example, at the fluences used in the demonstration above ($\approx$100 mJ/cm^2), an excimer laser with a total energy per pulse of 1 J could release structures over an area of 10 cm^2 in a single pulse.

Residual sacrificial material on released test structures was removed by RIE in an Oxford plasma technology RIE80. A suitable process was first established using masked polyimide layers on silicon. This resulted in the following process conditions being adopted: 50-mT pressure, 180-W radio frequency (RF) power, and 50-sccm oxygen. An etch rate of 0.51 μm/min was obtained, corresponding to an etch time of 6 min for a 3-μm sacrificial layer. RIE proved to be an effective cleaning method, although some care had to be taken to avoid dislodging released structures when evacuating and venting the process chamber. Inspection of released test structures and final substrates under an optical microscope revealed no evidence either of surface damage arising from the release step or of plastic deformation in the released structures.

To demonstrate the application of laser-assisted assembly to a microelectromechanical device, the technique was used to assemble arrays of wobble motors, based on the design proposed by Paratte and de Rooij [38], [39]. In this device, the rotor moves in the manner of a flipped coin, with the driving field occupying the region between the rotor and an underlying stator. The device is shown in cross section in Fig. 7(a). The stator comprises four nickel levels, which define: 1) a circular array of eight electrodes, with associated contact pads; 2) an annular spacer, which defines the minimum gap between the rotor and electrodes; 3) a bush to raise the rotor center; and 4) a shaft to guide the rotor motion. The rotor is a single-level structure fabricated on a separate substrate. Fig. 7(b) and (c) shows scanning electron microscope (SEM) photographs of the component parts prior to assembly. It is perhaps worth noting that the device could, in principle, be fabricated monolithically, using a five-level sacrificial layer process. However, UV-LIGA processes with so many levels are difficult to implement in practice due to the cumulative effects of height variations in the electroformed metal. Furthermore, extra features (probably requiring two further levels) would be needed to prevent loss of the rotor by fluid transport during wet chemical release.

Arrays of component parts were fabricated on 3-in silica wafers, and devices were laser assembled in step-and-repeat mode using a single initial alignment operation. Although each wafer contained 36 rotors or stators on a square grid (6-mm pitch), the maximum array size that could be assembled in this way was 4 $\times$ 4 because of the limited travel of the motorized stages. Fig. 7(d) shows a laser-assembled device at low magnification, while Fig. 7(e) shows four different devices from a single 4 $\times$ 4 array, covering two shaft sizes and two rotor designs (spoked and solid).

V. Discussion

We have demonstrated for the first time a laser-assisted batch assembly method for components formed on silica substrates with polymer sacrificial layers. The test structures used were in the size range where manual assembly would be difficult and time consuming and likely to result in permanent damage to the released parts.

As a general sacrificial release method, laser-driven release offers a number of key advantages over conventional sacrificial layer processing. First, it allows step-by-step release of individual components—or groups of components—from a single sacrificial layer. This type of sequential release could, in principle, be achieved with wet chemical processing, but only by having a number of different sacrificial materials. Second, wet chemical release is typically a slow process, with the time taken to release a given structure being strongly dependent on the size and shape of its footprint. This is because the etchant can attack the sacrificial material only by undercutting the structure. Laser-driven release, on the other hand, offers short release times (typically 1 ms or less) which are largely independent of geometry. Third, the laser release process avoids the use of wet chemicals, thereby avoiding unwanted motion of released components by fluid transport, surface tension effects during drying, and stick down.

Further work is required to determine the effects of fluence, beam homogeneity and ambient pressure on the inherent placement accuracy of the process, and the likelihood of damaging components. Excimer laser cleaning of released structures should also be investigated as an alternative to RIE, as this would be more compatible with laser-driven release. Cleaning of semiconductor substrates by exposure at low fluence has received growing interest over the past few years [40], and commercial laser cleaning machines are now available.

Another key area for future research is the extension of the laser-assembly technique to MEMS components which cannot be fabricated on UV-transparent substrates, for example, silicon-micromachined parts. Here, we require methods for transferring components, en masse, from their original substrates to appropriate carriers. This might, for example, involve bonding the entire array to a carrier using an epoxy resin and then removing the original substrate by wet etching (of either the substrate itself or a sacrificial layer). The epoxy would then act as a sacrificial layer for the laser-assisted assembly process.

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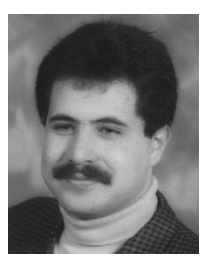

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