Micron 57 (2014) 56–66

Contents lists available at ScienceDirect

Micron

journal homepage: www.elsevier.com/locate/micron

The fabrication of aspherical microlenses using focused ion-beam techniques

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ARTICLE INFO

Article history:
Received 29 August 2013
Received in revised form 18 October 2013
Accepted 18 October 2013

Keywords:
Aspheric micro-lenses
Micro-fabrication
Focused ion beam lithography
Chemical etching

ABSTRACT

Aspheric lenses are the most common method for correcting for spherical aberrations but, in microlens production, highly-controlled lens profiles are hard to achieve. We demonstrate a technique for creating bespoke, highly-accurate aspheric or spherical profile silicon microlens moulds, of almost any footprint, using focused ion-beam milling. Along with this, we present a method of removing induced ion-beam damage in silicon, via a hydrofluoric acid etch, helping to recover the surface's optical and chemical properties.

In this paper, we demonstrate that our milled and etched moulds have a roughness of 4.0–4.1 nm, meaning they scatter less than 1% of light, down to wavelengths of 51 nm, showing that the moulds are suitable to make lenses that are able to handle light from UV up to infra-red.

Using empirical experiments and computer simulations, we show that increasing the ion-dose when milling increases the amount of gallium a hydrofluoric acid etch can remove, by increasing the degree of amorphisation within the surface. For doses above 3000 $\mu C/cm^2$ this restores previous surface properties, reducing adhesion to the mould, allowing for a cleaner release and enabling higher quality lenses to be made.

Our technique is used to make aspheric microlenses of down to 3 μm in size, but with a potential to make lenses smaller than 1 μm.

1. Introduction

Due to the growing overlap between electronics and optics, microlenses are becoming increasingly popular, finding use in enhancing the light-gathering ability of pixels in digital cameras (Bass, 1995) and in improving optical-fibre coupling efficiency in the communications industry (Leggatt and Hutley, 1991). In digital cameras, the ever decreasing size of camera pixels necessitates a novel method of directing light into sensing regions (Fesenmaier et al., 2008). With pixels nearing the diffraction limit, approaching 1 μm in size (Moon et al., 2007), the manufacture of high quality lenses of this size could dramatically improve the detector's quality and sensitivity.

Current manufacturing techniques involve using conventional photolithography to produce the large arrays of lenses needed, using the reflow technique (Roy et al., 2009). A block of photoresist is deposited and then subsequently melted, to form lens-like droplets. The profile of these lenses is controlled by the wettability of the surface by the photoresist material, allowing spherical or elliptical lenses to be formed. Whilst able to focus light, these lenses suffer from spherical aberration, reducing their ability to accurately direct light, and leading to pixel cross-talk and increased noise (Huo et al., 2010).

In the area of optical communications, fibre optic coupling is known to be an area fraught with alignment issues. The use of microlenses to aid in alignment was first demonstrated over 20 years ago, in 1991 (Leggatt and Hutley, 1991), showing an improvement in the transmissivity between fibres. However, the refractive lenses made by modern techniques also tend to suffer from spherical aberration, which is a major contributing factor to coupling inefficiency (Wilson, 1994). This reduces the alignment gain achieved when using microlenses.

Correcting spatial aberration through lens shape design can therefore lead to significant advances in improving the quality and the sensitivity of digital image detectors and in optical communications. The most common method of overcoming spherical aberration on the macro-scale is to use a parabolic or hyperbolic lens profile, two shapes that self-correct for such aberration (Mahajan, 1991). When manufacturing micro-lenses via conventional reflow, there is limited control over the lens profile, so

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http://dx.doi.org/10.1016/j.micron.2013.10.013

making parabolic lenses has proven difficult. Whilst attempts have been made using liquid crystals (Commander et al., 2000), mask shading techniques in vacuum deposition (Gunwald et al., 1998), electrostatic pulling and electrophoretic forces (Wang et al., 2011; Wu et al., 2011) among other methods, exotic profiles are still difficult to attain.

Focused ion-beam lithography (FIB) may hold the key, with its ability to precisely sculpt surfaces at both the nano- and micro-scales. Milling of micro-lens moulds for the creation of polymer lenses been demonstrated before (Fu, 2001), as has direct milling of microlenses onto optical fibre ends (Schiappelli, 2004). In both cases, the process suffers from two main problems: slow speed of milling and ion implantation damage. The speed of milling is not such a huge problem when putting lenses on optical fibres, as milling single lenses is a process of minutes to tens of minutes. For large arrays of lenses, the time taken to mill will be long, but by replicating the mould itself using nano-imprint replication, the mould only needs to be milled once to allow vast numbers of lenses to be manufactured (Nussbaum et al., 1998).

The second downside of FIB lithography is the damage and ion-implantation caused to the substrate surface during conventional milling. In crystalline silicon (c-Si) the ion beam amorphises the surface, creating an amorphous silicon (α-Si) layer (Rubanov and Munroe, 2004). The ion used for milling, most commonly gallium (Ga), can be found implanted in very high numbers at the surface. This reduces the transmisivity of the surface of the substrate (Fu et al., 2005; Howe et al., 2009). In directly-milled surfaces, this can lead to a higher degree of light absorption in the material (De Ridder et al., 2007), whilst in nano-replication, the milled regions are known to adhere more strongly to the soft polymers used, necessitating a thin metal coating to allow for uniform removal. Whilst this overcomes adhesion issues, it does not allow for high temperature treatments, such as thermosetting polymers, as it causes the Ga to diffuse to the Si-metal interface. It also is not a useful technique when looking at direct milling of optical elements, as it only augments the problem of reduced transmission through a Ga-implanted substrate. This means that removing the Ga and reducing the size of the amorphous silicon (α-Si) region restoring crystallinity are desirable for good quality, bespoke optics.

The most common method for removing this damage is a simple annealing process, to force the gallium to diffuse out of the surface, whilst recrystallising the substrate (Chyr et al., 1999; Schilling et al., 2007). However, this has been shown somewhat unsurprisingly to lead to Ga diffusing into the bulk (Sato et al., 2004), whilst the expelled Ga forms a hard GaO layer, causing both optical and adhesion problems when replicating, and therefore requiring further steps to remove (Mikkelsen et al., 2009).

In this paper, we start by demonstrating a novel method of manufacturing microlens moulds using focused ion-beam (FIB) lithography. Due to the difficulty in removing replicated lenses from the as-milled topography, we then investigate how chemical etching can be used to remove implantation damage and restore the surface properties, with minimal changes in shape and roughness. Previous papers have shown that Ga implanted Si etches vigorously in Hydrofluoric acid (HF) (Kawasegi et al., 2006) and is an etch stop to potassium hydroxide (KOH) (Böttger et al., 2011). Whilst a use for this has been demonstrated in nanofabrication, here, we show that this technique can be used as a simple method to remove ion implantation damage.

We will discuss the effect HF etching has on the dish profile and roughness, and the effect this has on the optical properties of the dish, which is a useful measure of the quality of the lenses moulded from these dishes may have. By then moving on to look at very low dose Siemens star patterns, we investigate the effect dose plays on etch depth, to help us predict how the shape of milled dishes will change when HF-etched. Comparing this information to computer simulations gives us an idea of the surface amorphisation required to successfully etch, which helps us calculate the percentage Ga left in the surface post-etch. Finally we confirm whether the implanted gallium is removed during etching via cross-sectional scanning transmission electron microscopy (STEM) with energy dispersive X-ray (EDX) mapping. We demonstrate that wet chemical etching successfully removes implanted gallium, restoring the surface properties closer to the original state. We show that HF etching is more effective at removing Ga at a high dose.

2. Method and theory

2.1. The ion-beam milling of a paraboloid

In focused ion-beam milling, the depth milled in any region is controlled by the dose of ions to which an area is exposed. Due to a linear relationship between depth and dose in silicon, any region exposed to a controlled dose will sputter to a known depth (Hopman et al., 2007). This also gives the advantage that the depth for multiple patterns milled in the same place will be a summation of the individual pattern depths.

The dose is controlled by the dwell time, beam current and number of passes the beam makes over an area. Increasing the dwell time in a single-pass pattern results in a non-linear increase in depth for long dwell times (Lehrer et al., 2001), caused by the increasing difficulty of removing material from deeper structures (as noted in the method section of the paper). By increasing the number of passes made, the total dwell time of all passes can be the same as a long dwell time, but the depth of the structure increases linearly. By better re-distributing the redeposited material, a higher number of passes also creates a much smoother dish.

Our technique makes use of this by first splitting the dish into a series of concentric entities, milling from smallest to largest, whilst linearly increasing the dose, such that the summation of the entity depths follows a parabolic function.

This method allows for the milling of any footprint as a set of concentric shapes, such as circles or n-sided polygons. In Fig. 1 we show how increasing the depth starting with the smallest entity in the pattern achieves an approximately parabolic profile. In theory this leaves a step edge, creating areas where the surface is either above or below the parabolic shape required. However, due to an edge effect whilst milling the sharp peak of the corners will be eroded more quickly than the surrounded area. Some of the sputtered material caused by milling will redeposit, filling in the corners which dip below the parabolic function. We have found only a small number of circles are necessary in the pattern to create a smooth profile, from 10 to 30 circles for 1 to 10 μm dishes.

As the dose is calculated by a combination of the ion-beam current (which is intrinsically linked to the beam spot size) and the dwell of the spot, the choice of beam current controls the speed of milling for a certain shape. Most of the dishes that we have manufactured have been milled at 50–300 pA, at an accelerating voltage of 30 kV, optimising the beam spot size for smoothness of the dish, whilst keeping milling times to a minimum.

When designing a pattern before milling, we must consider the dimensions of a parabolic dish. The focal length of a parabolic dish, F_D, can be found from the diameter of the dish, D, and its depth, c, linked by Eq. (1):

$$F_D = \frac{D^2}{16c} \tag{1}$$

From Eq. (1), the equation for the focal length of a plano-convex parabolic lens moulded from such a dish can be derived. The