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Microsphere Formation Using an Excimer Laser

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Abstract: *Silicon microspheres 800 nm to 10 μm have been formed using an excimer laser. The method described in this paper shows that microspheres can be formed with high yield and free of contamination. Silicon microspheres enable new applications where silica microspheres fall short. Due to their semiconducting properties, new photonic devices can be developed for nano-electro-optical applications.*

Keywords: *excimer, MDR, microcavity, microsphere, resonators, silicon photonics, WGM*

I. Introduction

The need for low-cost photonic devices has stimulated a significant amount of research in silicon photonics. Although silicon photonics is less well-developed as compared to III–V technologies, it has the potential to make a huge impact on the optical communications industry. Silicon is transparent in the standard ITU optical communication bands, which makes silicon the material of choice for passive and active optoelectronic devices. Recently, microspheres are gaining an important place in the optical microcavity resonator community due to their high quality factor morphology-dependent resonances (MDRs). Silicon microspheres with high quality factor morphology dependent resonances are used for resonant detection and filtering of light in the near infrared. The experimentally measured quality factors are limited by the sensitivity of the experimental setup, however, the microsphere quality factor is several orders of magnitude higher than current micro-ring resonators. These optical resonances provide the necessary narrow linewidths that are needed for high resolution micro-photonic applications. Potential applications that silica microspheres have been identified for include microlasers [1], channel dropping filters [2], [3], optical switching [4], ultrafine sensing [5], displacement measurement [6], rotation detection [7], high-resolution spectroscopy [8] and Raman lasers [9]. On the other hand, although silica is known to be an insulator, silicon can be doped to be electrically active. Therefore, silicon microspheres would extend the applications list to include solar cells, light emitting diodes, or other semiconducting devices. A reproducible process to quickly fabricate uniform microsphere particles with a narrow distribution of diameters and high yield is presented in this paper. Currently, the typical methods used to form microspheres include forcing molten silicon out of a nozzle [10] or melting the end of a fiber [1].

II. Experiment

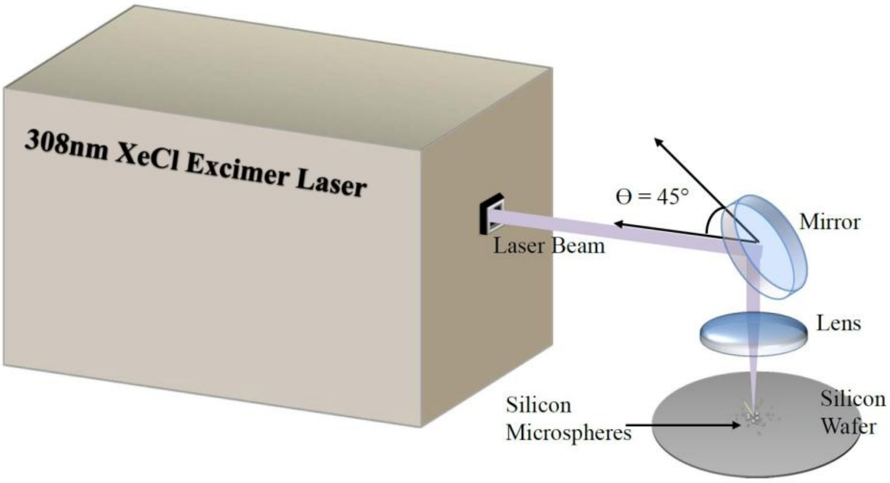

Figure 1. Experimental setup for silicon microsphere fabrication

The silicon microspheres were created by using a 250-watt, 308 nm XeCl excimer laser (Lambda Physik L4308, 1 Joule per pulse max). The output beam profile of the excimer laser is 3cm by 1cm. The beam is reflected downward with a 45 degree mirror and focused into either a 3cm long line profile using a cylindrical lens or a point profile using a spherical lens with both lenses having a 20cm long focal length as shown in Fig.1.

The focused beam impinges onto a silicon wafer at a rate of 100 pulses per second with the wafer resting upon an automated X-Y translation stage (Aerotech ATS10015-M).

The high intensity of the impinging beam ablates the silicon off the exposed wafer surface as micro-particulates. The micro-particulates may or may not be molten as they are ejected from the surface of the silicon wafer. A container is used to surround the ablated area to prevent the micro-particulates from ejecting off the stage. The translation stage is required to ensure the focal point of the beam is always focused on the surface of the wafer. A high speed 400 frames per second infrared camera (FLIR SC4000) was used to determine the velocity of the micro-particulates ablated from the wafer surface.

III. Results

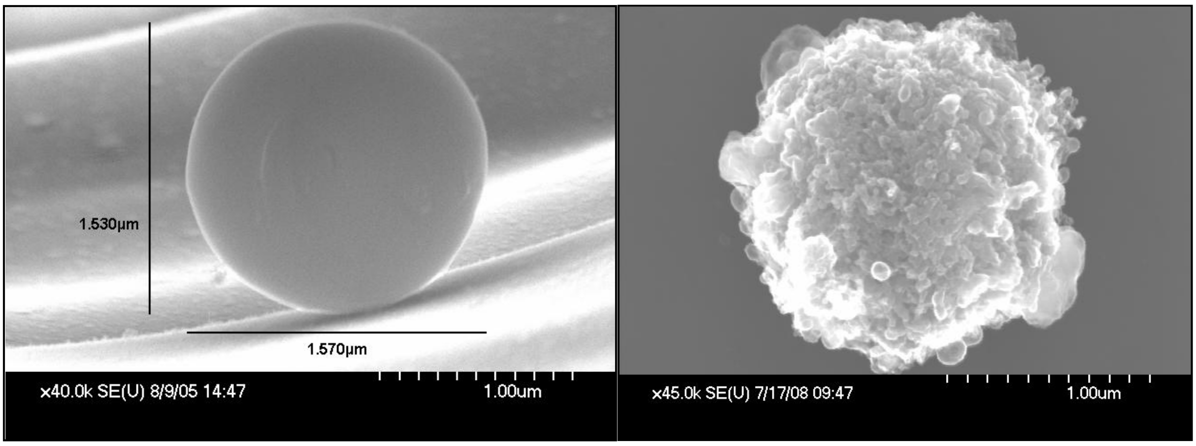

Figure 2. Scanning electron microscope image of a silicon microsphere created by using (a) a cylindrical lens (*left*) and (b) a similar sized particle created using a spherical lens (*right*).

Microspheres are formed when a molten droplet of material solidifies as it is suspended in air. The physics due to surface tension is the basis for the formation the near perfectly spherical particles with re-solidification times of less than a nanosecond [11]. Using a cylindrical lens, Fig. 2 (a) shows a scanning electron microscopy image of a 1.5 micron diameter silicon sphere created using 500 mJ for the output energy. This translates to energy density of approximately 16 J/cm^2 for a focused beam width of 0.1 mm. For a spherical lens, an energy density upwards of 50 J/cm2 can be achieved for a 1 mm by 1 mm focused spot size. Interestingly nearly all particulates generated with a spherical lens produced irregularly shaped particles as shown in Fig. 2 (b).

From these results, it can be deduced that the particulates are partially molten when they are ejected from the surface and that smooth microspheres only form when the ablated particulates re-enter the beam at least one additional time, ensuring the particulate is in a molten state in the form of a liquefied droplet. The longer line beam profile produced by the cylindrical lens facilitates a greater chance for the particulates to re-enter the beam multiple times and therefore produces a much higher yield of microspheres. In comparison, the spherical lens produces a very narrow beam and only particulates which have been ejected exactly normal to the plane of the surface will liquefied. From these observations, it can be concluded that a cylindrical lens produces the best results for the fabrication of silicon microspheres.

For single crystal silicon, it is well known that the optical phonon dispersion curve contains one Raman active zone center phonon at 523 cm^{-1}. For amorphous silicon, the Raman spectrum will be shifted from the single crystal center frequency as well as broadened due to the plethora of zone center phonons. Raman Spectroscopy was performed on the silicon microsphere to determine its microstructure. The peak at 523 cm^{-1} as shown in Fig. 3, indicates that the microspheres are single crystalline.

The maximum production rate was measured for this microsphere formation technique. A laser energy of 700 mJ and a repetition rate of 300 pulses per second and a translation stage rate of 5 cm/s was used to measure the maximum amount of particles achievable with this method. The particles were collected and weighed on a Mettler balance scale where it could then be calculated that the maximum particle production rate was approximately 2000 mg/hr. For laser systems that have a higher repetition rate limit beyond 300 pulses per second, the rate of production can be increased further. Fig. 3 (a) shows the microsphere yield results of a laser energy set to 500 mJ at 100 Hz. When compared to the yield results of a laser energy set to 700 mJ at 100 Hz as shown in Fig. 3 (b), it can be immediately noticed that the lower energy beam produces smaller microspheres on the order of 1 to 2 μm while an increase in laser energy shows larger microspheres up to 10 μm in diameter. This can be attributed to the fact that larger particulates have been ablated from the surface and rendered molten through multiple passes through the beam.

The velocity of the particulates ejected from the silicon wafer needs to be known to determine the minimum pulse rate of the excimer laser. The minimum pulse rate would ensure that the ejected particulate would pass through the beam at least one time. The ejection velocity of particulates was determined with the use a high speed infrared camera. A grid of known space was placed in the background and with the known number of 400 frames per second, the velocity of the particulates was measured at approximately 3.8 m/s. Given that the laser pulse width is 20 ns, the beam would be 6 m in length. Assuming that air resistance is negligible, and for particles ejected through the 3 cm beam lengthwise, the particle would pass through two pulses of the beam at a repetition rate of 300 Hz. In order to ensure that the majority of particles are collected, a thin rectangular container was used to surround the beam, this also increase the chances of the particles to pass through multiple beams as it bounces of the container walls.

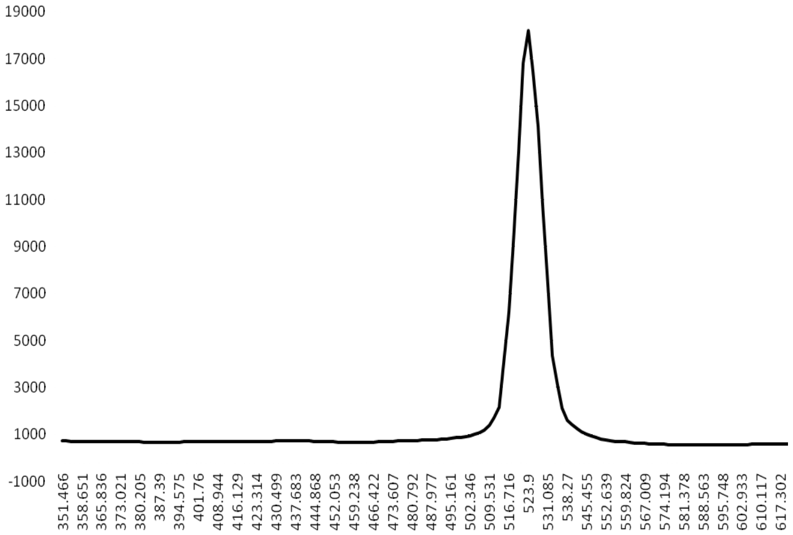

Figure 3. Raman spectroscopy measurements on silicon microspheres with vertical and horizontal axis representing the 'intensity' (a.u.) and 'Raman shift' (cm^{-1}), respectively.

IV. Conclusion

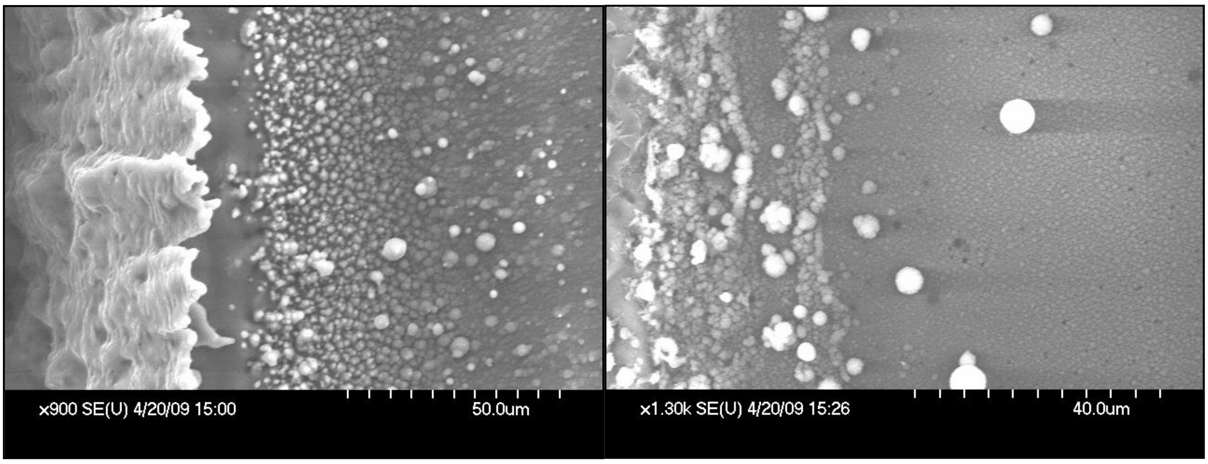

Figure 4. Microspheres formed using an excimer laser energy of (a) 500 mJ (*left*) and (b) 700 mJ (*right*).

A novel high yield method of forming silicon microspheres has been shown using an excimer laser. It has been concluded that the formation mechanism is due to the ablated particulates remelting as they pass through the laser beam and the surface tension enforces the spherical shape during resolidification. The result is nearly perfectly spherical microspheres with diameters range from 800 nm to 10 μm. Raman spectroscopy indicates that these microspheres are single crystalline. Future work includes developing a sorting process using optical radiation pressure and optical characterization to determine their suitability for optical resonator applications.

Acknowledgements

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