

In Vivo Biostability of CVD Silicon Oxide and Silicon Nitride Films

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ABSTRACT

Low pressure chemical vapor deposition (LPCVD) and plasma enhanced chemical vapor deposition (PECVD) silicon oxide and silicon nitride films were implanted subcutaneously in a rat model to study *in vivo* behavior of the films. Silicon chips coated with the films of interest were implanted for up to one year, and film thickness was evaluated by spectrophotometry and sectioning. Dissolution rates were estimated to be 0.33 nm/day for LPCVD silicon nitride, 2.0 nm/day for PECVD silicon nitride, and 3.5 nm/day for PECVD silicon oxide. A similar PECVD silicon oxide dissolution rate was observed on a silicon oxide / silicon nitride / silicon oxide stack that was sectioned by focused ion beam etching. These results provide a biostability reference for designing implantable microfabricated devices that feature exposed ceramic films.

INTRODUCTION

Microfabricated devices have been used in a variety of biomedical implant applications, including neural stimulation, sensing, and drug delivery. These devices often rely upon exposed conductive and dielectric films for operation. For example, microchips have incorporated LPCVD or PECVD ceramic films, most commonly silicon oxide and silicon nitride, to selectively passivate electrodes against the *in vitro* and *in vivo* environments [1-3]. These films have also been used as insulating layers between metal features and a silicon substrate. In some applications, silicon oxide and silicon nitride films have been combined to act as a barrier to ion transport [4] or to balance opposing residual stresses [5].

Silicon oxide and silicon nitride are known to dissolve in aqueous media [6-8]. At the hydrated surface of the film, silicon oxide dissolves to form aqueous $\text{Si}(\text{OH})_4$. Si-O bonds replace Si-N bonds in silicon nitride films, releasing NH_3 into the surrounding medium. There have been previous reports of the dissolution rate of CVD dielectric films in saline with a focus on ranking material candidates *in vitro* [9].

An additional complication for implanted devices is exposure to a complex biochemical environment composed of blood or interstitial fluid along with a transient chemical profile due to wound healing [10]. The biological response to any implanted medical device is a function of the physical characteristics of the device, the properties of the fabrication materials, the location of the implant, and the skill of the surgeon. The normal tissue response to an injury follows a well-established series of cellular and biochemical pathways, beginning with infiltration of polymorphonuclear leukocytes into the site, followed by the appearance of macrophages and fibroblasts. In the subcutaneous space, a fibrous capsule consisting primarily of collagen eventually forms around the device.

The corrosive *in vivo* environment promotes dissolution of ceramic films, leaving electrodes unprotected from degradation mechanisms such as delamination and corrosion. Structures that rely on stress-compensating layers may undergo deformation as the films gradually dissolve.

Because a film dissolution rate as low as one micron per year could affect device performance, an understanding of thin film biostability is fundamental to extending the useful life of microfabricated implants.

We report here on the *in vivo* dissolution of LPCVD and PECVD silicon nitride films and PECVD silicon oxide films deposited on a silicon substrate. A biostability study was performed by implanting these films in the subcutaneous space of a rat model for up to twelve months. Dissolution rates were obtained by spectrophotometry and by scanning electron microscopy (SEM) cross sections of explanted chips. Cross-section images were also acquired by focused ion beam (FIB). FIB sectioning is useful when characterizing *in vivo* degradation because it does not require polishing or wet chemical etching, which are often used to delineate layers in cross sections. These sample preparation steps can distort features and create voids that can be confused with the effects of *in vivo* exposure.

MATERIALS AND METHODS

Film preparation

Silicon nitride was deposited on a 4-inch silicon wafer by LPCVD at a temperature of 800-850°C to a nominal thickness of 0.20 μm . The gas precursors were SiH_2Cl_2 and NH_3 in a mass flow ratio of greater than 3:1, which produced a silicon-rich film with a residual tensile stress of <120 MPa. The refractive index was measured by ellipsometry (Woollam V-VASE) to be 2.25 at a wavelength of 633 nm, and the actual film thickness was measured by spectrophotometry (Nanometrics Nanospec AFT) to be 0.21 μm .

Single layers of silicon oxide and silicon nitride were deposited on 4-inch silicon wafers by PECVD (PlasmaTherm System VII 790 Series) to a nominal thickness of 1.0 μm each. The deposition temperature for both films was 350°C. The precursors for the silicon nitride film were SiH_4 , NH_3 , He, and N_2 , and the deposition rate was 12.5 nm/min. The refractive index and actual thickness were found to be 2.03 and 0.99 μm , respectively. The precursors for the silicon oxide film were SiH_4 , N_2O , He, and N_2 , and the deposition rate was 36 nm/min. The refractive index and actual thickness were found to be 1.47 and 1.06 μm , respectively.

A patterned wafer was also fabricated with a 1 μm silicon oxide / 1 μm silicon nitride / 1 μm silicon oxide stack deposited by PECVD over metal features that had been deposited by sputtering and patterned by wet etching. This stack was in turn covered with additional patterned metal features to selectively mask the ceramic films from the *in vivo* environment.

Implant assembly

The wafers were diced to produce 7.5x7.5 mm² chips. The chips were then rinsed with acetone, methanol, isopropyl alcohol, and deionized (DI) water, and dried with filtered compressed air. Titanium carriers were cleaned by sonicating in acetone, ethanol, and Liquinox[®] for 30 minutes each and rinsing in DI water after each step. The chips were assembled in titanium carriers as shown in Figure 1. A silicone gasket was placed between the carrier and the chip, and silicone potting was placed around the chip-carrier interface and screw heads. The assembled carriers were then terminally sterilized with ethylene oxide gas.

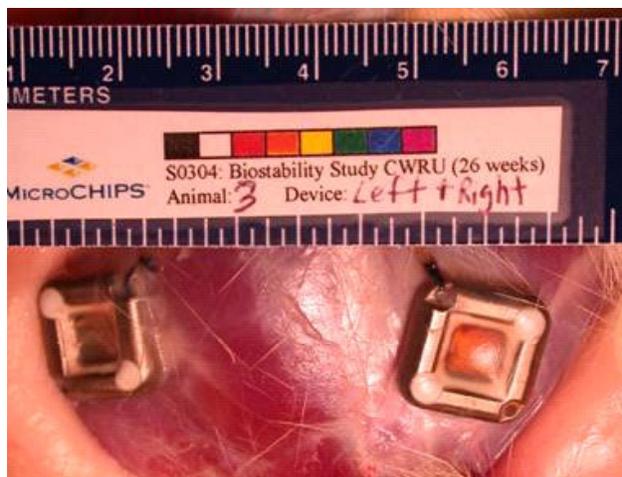
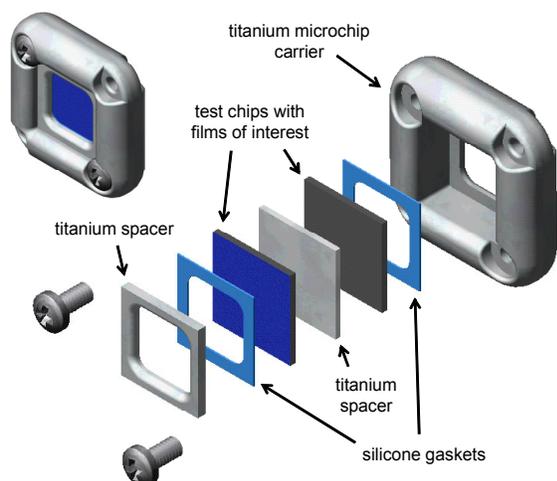


Figure 1. Chip carrier for biostability studies. **Figure 2.** Device appearance at explantation.

In vivo work

Female Sprague-Dawley rats less than one year old were anesthetized with an IP injection of ketamine, xylazine, and acepromazine, and the dorsal region was clipped and prepped for surgery. A single dorsal midline incision was made lateral to the spine, and blunt dissection used to create pockets in the subcutaneous space over each flank. The devices were implanted in the subcutaneous space of the dorsal flank and sutured against the fascial layer. The implant site was then sutured closed. At the desired time point (1, 3, 6, or 12 months), the animals were euthanized, and the devices and the surrounding fibrous capsules were recovered. The fibrous capsules were removed from the surface of the carriers by cutting around the perimeter, then peeling back the tissue. A picture of two devices before the fibrous capsules were removed is shown in Figure 2. The devices were immersed in Tergazyme[®], an enzymatic cleaning solution, for approximately 24 hours at room temperature to remove residual organic material. The devices were then rinsed in ethanol and DI water, dried with nitrogen, and sterilized for thirty minutes in a steam autoclave at 121° C and 2 atm. It was determined from spectrophotometry measurements on non-implanted chip controls that Tergazyme immersion and autoclaving had no statistically significant effect on film thickness.

Film analysis

Film thickness after explantation was evaluated by spectrophotometry, with measurements taken at the center of the chips. Spectrophotometry requires the refractive index to be known. The value obtained by ellipsometry before implantation was used for these measurements. SEM was also used to evaluate film thickness to verify the spectrophotometry results. One chip from each time point was cleaved to expose a cross section through the center of the chip, and the cross section was imaged by SEM. The uncertainty in thickness measurements from these SEM images is estimated to be $\pm 5\%$.

Cross sections of the 3 μm silicon oxide / silicon nitride / silicon oxide stack were acquired by FIB (FEI dual-beam model 830). A 0.5 μm thick platinum line was deposited along the sectioning line as a sacrificial layer before sectioning. Images were then acquired by SEM.

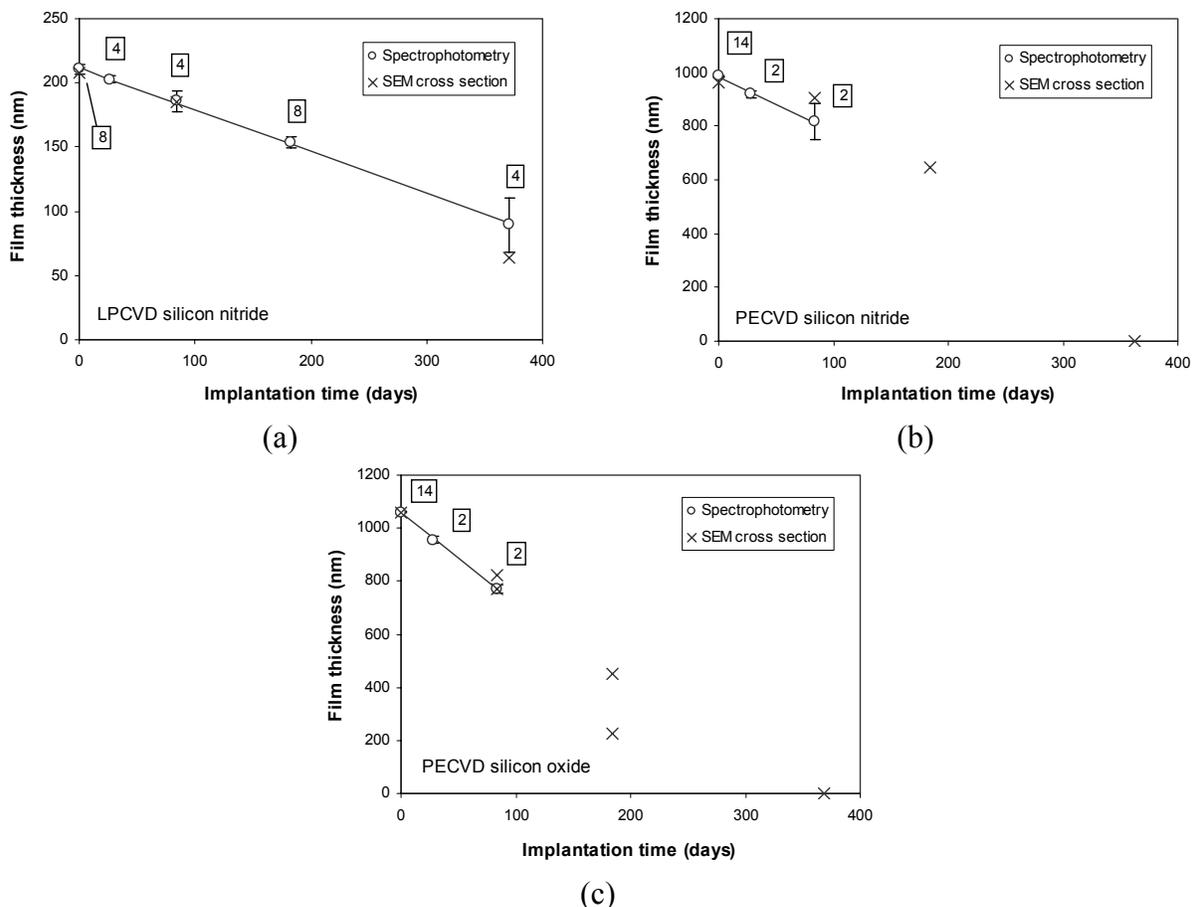


Figure 3. (a) LPCVD silicon nitride, (b) PECVD silicon nitride, and (c) PECVD silicon oxide film thickness versus implantation time as measured by spectrophotometry and SEM cross sections. The number of spectrophotometry samples is shown in the boxes, and error bars indicate the first standard deviation of data. The lines are fit to the spectrophotometry data.

RESULTS AND DISCUSSION

The changing film thickness of LPCVD silicon nitride as measured by spectrophotometry and SEM cross sections is shown in Figure 3(a). The number of samples is shown in each box, and error bars indicate the first standard deviation of the spectrophotometry data. The data suggest a linear trend of decreasing thickness with implantation time, and a line was fit to the spectrophotometry data by least squares. The average *in vivo* dissolution rate for LPCVD silicon nitride is estimated to be 0.33 nm/day.

Thickness measurements of a PECVD silicon nitride film as measured by spectrophotometry and SEM cross sections are shown in Figure 3(b) (only the first three months of spectrophotometry data were available for the PECVD films). The average dissolution rate is estimated to be 2.0 nm/day. The film had completely dissolved on the cleaved sample from the 12-month time point that was imaged by SEM. However, the film had not yet completely dissolved on the other sample from that time point.

Thickness measurements of a PECVD silicon oxide film are shown in Figure 3(c). The average dissolution rate is estimated to be 3.5 nm/day. Some pitting was observed on the cross-

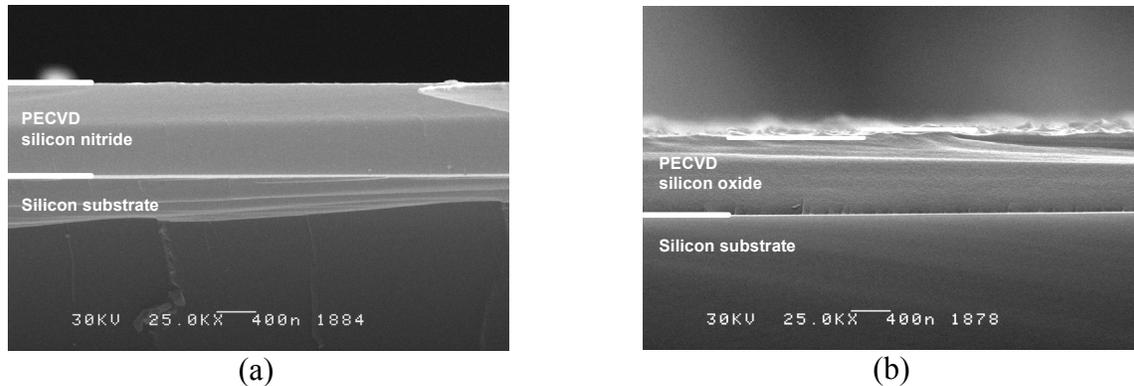


Figure 4. Micrographs of (a) PECVD silicon nitride and (b) PECVD silicon oxide cross sections after three months implantation.

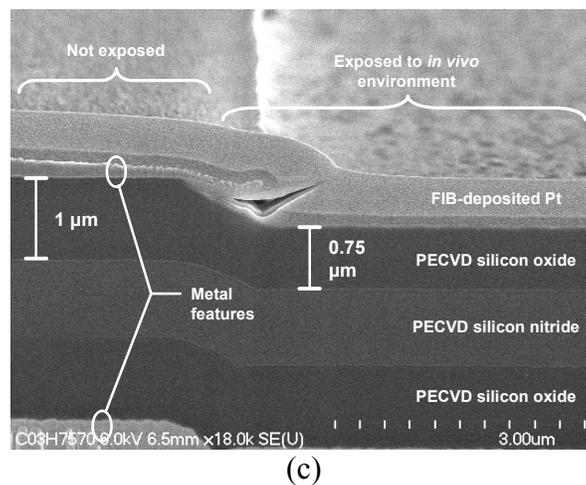


Figure 5. Micrograph of PECVD silicon oxide / silicon nitride / silicon oxide stack after three months implantation and sectioning by FIB. A metal feature over part of the film (left side) protected that part of the film from dissolution during the implant period.

section images of the PECVD film. Two film thickness values, representing the maximum and minimum measurements, are therefore given for both the three-month and six-month time points in Figure 3(c). The minimum thickness values are of particular interest, since they provide an indication of when the substrate or underlying material will be exposed. This information complements the spectrophotometry data on average film thickness.

The 1 μm PECVD silicon oxide film had completely dissolved on both samples from the 12-month time point. Hämmerle *et al* reported a similar dissolution rate, approximately 1 $\mu\text{m}/\text{year}$, for a 0.5 μm silicon oxide film deposited by LPCVD at a temperature of 395°C with tetraethylorthosilicate (TEOS) as a precursor gas [2]. That group observed almost complete film dissolution in six months for a subretinal implant location. Hetke *et al* reported that a 0.4 μm silicon oxide / 0.2 μm silicon nitride / 0.4 μm silicon oxide stack deposited by LPCVD lasted over one year, but no dissolution rates were reported [5].

SEM cross sections of PECVD silicon nitride and silicon oxide films after implantation for three months are shown in Figure 4(a) and Figure 4(b), respectively. The maximum and minimum thickness locations are indicated for the silicon oxide film. A micrograph of the three-layer stack taken after FIB sectioning is shown in Figure 5; this device was implanted for three

months. It is estimated that approximately 0.25 μm of the PECVD silicon oxide film dissolved in this time; this result agrees with the single-film data shown in Figure 3(c).

CONCLUSIONS

The biostability of LPCVD silicon nitride and PECVD silicon oxide and silicon nitride films was investigated. Chips with patterned and unpatterned films were implanted subcutaneously in a rat model for different times, and the change in film thickness over time was evaluated using spectrophotometry and SEM of cross sections. Spectrophotometry provided a non-destructive way to measure average film thickness, while SEM images allowed variations in thickness to be observed. Dissolution rates were extracted from the thickness data. Focused ion beam sectioning was found to be useful for acquiring high-quality images of multiple ceramic films that might otherwise be difficult to characterize after a period of implantation.

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