VACUUM-SEALED SILICON MICROMACHINED INCANDESCENT LIGHT SOURCE

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ABSTRACT

We have fabricated a silicon-filament vacuum-sealed incandescent light using technologies and materials derived from IC processes. The incandescent source consists of a heavily-doped p⁺ polysilicon filament coated with silicon nitride and enclosed in a vacuum-sealed cavity. The filament is electrically heated to reach a maximum temperature between 1500 and 1600 K corresponding to a peak blackbody wavelength at approximately 2 μm. The power required to achieve this temperature in a filament 350 × 3 × 1 μm² is 3.5 mW. The cavity is sealed with a silicon-nitride window that is highly transmissive to the emitted radiation. The microlamp can be processed compatibly with circuits and has been operated in a liquid ambient. Without substrate cooling, it requires several ms for complete turn-off after being disconnected from power.

INTRODUCTION

Incandescent blackbody-radiation sources have a number of applications. For example, in chemical analysis, the wideband spectrum of these sources is useful to analyze the light absorption of samples. Other potential uses are in displays, infrared scene generation, and the calibration of photosensors.

Miniaturized incandescent sources, consisting of thin-film tungsten filaments suspended from a glass substrate and fabricated using hybrid-circuit techniques, have been used for displays [1,2]. Recently, miniature incandescent light sources [3,4] made with IC-derived processes have been described. In these devices, the incandescent filaments were made from polycrystalline silicon, either uncoated [5] or else coated with a special low-residual-strain silicon-nitride film. These filaments stood one or two micrometers above the silicon substrate and were exposed to the ambient environment.

We discuss the fabrication and operation of an IC-processed incandescent microlamp in which the filament is encased in an individual vacuum cavity as shown in the cross-sectional sketch of Figure 1.

The cavity is sealed on the upper surface by a window that is transparent to the incandescent blackbody radiation. Vacuum sealing provides a microlamp that is not subject to continued oxidation or contamination problems and that can be fabricated at an early stage and protected during further wafer processing steps. This provides added flexibility in fabricating microlamps and integrated circuits on the same chip. The quality of the microsealed cavity is demonstrated by the observed operation of microlamps which are submerged in water.

MICROLAMP STRUCTURES

In the structure of Fig. 1, the incandescent filament is placed in a cavity bounded by an anisotropically-etched silicon V-groove in the substrate surface and a low-stress silicon-nitride window [6,7]. The window hermetically seals the cavity at the time of the silicon-nitride deposition. The V-groove silicon walls of the cavity are partial reflectors for the photons radiated from the filament. The V-groove is approximately 25 μm deep.

The thermal radiator consists of a p⁺ polysilicon filament coated with low-stress silicon nitride. The conductive polysilicon and insulating silicon-nitride coating are 0.9 μm, and 0.3-0.5 μm thick, respectively. Filament lengths from 110 to 510 μm (40 μm intervals) have been made in a single wafer run. In operation, a selected microlamp filament is resistive heated until it glows.

The cavity seal is achieved filling lateral etch channels [8,9] with additional silicon nitride after the filament has been released and the V-groove etched. The pressure inside the sealed chamber is initially the same as that during the silicon-nitride deposition (300 mT at 835 °C), but can become lower owing to gettering action when the filament is heated. A similar technique has been used by Sugiyama et. al. [9,5] for the fabrication of an absolute pressure sensor. The silicon-nitride window must be thick enough to undergo negligible deflection due to the pressure difference between the chamber and the outside environment. Window thicknesses of 2.5-2.8 μm, as used for our microlamps, met this criterion.

Figure 2 shows a photograph of the top view of three vacuum-sealed microlamps of differing lengths. The microlamp shown in Figure 3 has been punctured intentionally to reveal the filament beneath it. It is seen in the Fig. that the filament is completely isolated from the external environment. Figure 4 shows an SEM photograph of a cleaved cross-section through a microlamp. The filament inside the lamp cavity is broken and therefore unsupported on one end, but the picture distinctly shows that it is clear of the bottom of the window and of the V-groove walls. Figure 5 shows the cross section of a microlamp near a sealed etch channel. The etch channel is seen to have been completely filled with silicon nitride. The surface of the silicon nitride near the etch-channel seal is very smooth with no evidence of cracks. Two four-inch wafers, each containing more than 2000 microlamps, have been fully processed (other wafers are partially completed). Thus far, all microlamps tested have functioned properly under bias.

Fig. 1. Sketch of the cross section of a vacuum-sealed microlamp.
Fig. 2. Top view of three vacuum-sealed microlamps 390, 430, and 470 μm long. The silicon-nitride windows are 55 μm wide.

Fig. 3. Top view of a microlamp in which the silicon-nitride window has been punctured to reveal the filament. The alternating patterns surrounding the window show the etch holes and anchors.

Fig. 4. SEM photograph of a cleaved microlamp showing that the filament inside the cavity is not bonded to the window or cavity walls. The depth of the V-groove is approximately 25 μm.

Fig. 5. SEM photographs of a microlamp cross-section near a sealed etch channel showing the seal to be complete and free of cracks.

FABRICATION

The main steps in the microlamp fabrication process are shown in Fig. 6. The 7-mask process starts with a <100> silicon wafer on which a thin layer of low-stress silicon nitride is deposited. This 0.5 μm-thick layer is etched to define the edges of the silicon V-groove and the etching is followed by a deposition of 0.7 μm of phosphosilicate glass (PSG) to provide a spacer layer [9] between the filament and the substrate. A 0.3 μm layer of low-stress silicon nitride [7] is then deposited which will form the base of the filament. After the deposition, the residual oxide of the silicon nitride is removed by an HF dip, and 0.9 μm of undoped polysilicon is grown. The wafer is then ion implanted with $10^{16}$ cm$^{-2}$ of boron, yielding a resistivity of $4 \times 10^{-3}$ Ω·cm after annealing. The polysilicon filament is then patterned with plasma etch, stopping at the nitride layer.

Again, the residual oxide on the bottom silicon-nitride layer is carefully removed and a 0.3 μm layer of low-stress silicon nitride is deposited to form the upper part of the filament seal. The top and bottom silicon-nitride layers are next patterned and etched to form a coating around the filament. The silicon-nitride etching stops at the oxide spacer as shown in Fig. 6(b).

A 3 μm-thick layer of PSG is then deposited to form a glass mesa on top of the filament. The wafers are heated at 1050 °C for 30 minutes to activate the filament dopants and to reflow the thick PSG layer. After the reflow, the PSG mesa is etched in buffered HF. The reflow step is necessary to achieve a satisfactory etch of the PSG mesa.

After the mesa is formed, a subsequent deposition of 0.8 μm of PSG is performed and the glass is patterned with buffered HF to form an alternating row of etch channels [8] and anchors for the silicon-nitride window as seen in the photograph of Fig. 4. If desired, the height of these channels could be reduced. Sugiyama et. al. [9] produced satisfactory cavities using 0.15 μm-high channels.

After the PSG etch, a 1 μm-thick layer of low-stress silicon nitride is deposited. This layer, which represents approximately one half of the thickness of the silicon-nitride window, is then patterned and etched (on the periphery of the microlamp) down to the PSG of the etch channels as shown in Fig. 6(c). These nitride openings are etch holes through which the sacrificial PSG and silicon substrate will be etched.

After the etch holes have been opened, the samples are immersed in concentrated HF for 2.5 minutes to remove the PSG under the silicon-nitride window. The wafers are then immersed in hot KOH for 90 minutes to etch the V-groove in the silicon substrate. The samples are cleaned and an additional layer of silicon nitride is deposited.
filling the etch holes and hermetically sealing the cavity containing the filament. After this step, contact holes to the polysilicon filaments are opened, and the wafers are metalized and sintered.

Fig. 6. Simplified fabrication process: (a) initial spacer deposition, (b) nitride-coated filament deposition and definition, (c) PSG mesa and etch-channel definition, (d) nitride-window deposition and etch-hole definition, (e) PSG removal and silicon-groove etch, (f) etch holes sealed with additional nitride.

MEASUREMENTS
Stoichiometric silicon nitride is transparent [10, 11] to radiation with wavelengths between 0.28 and 8 μm. The low-stress silicon nitride window is not stoichiometric [7] having a composition of Si₀.₆N₁.₄ and a refractive index of 2.4. Figure 7 shows the optical transmission of a 1.3 μm-thick low-stress silicon-nitride membrane measured using a FTIR spectrophotometer. The oscillatory nature of the transmission is caused by interference in the thin membrane. The nitride is transparent between 0.5 to 8 μm; hence it transmits most of the radiation emitted by the incandescent filament. The increase of the lower wavelength absorption edge in the low-stress nitride compared to that of the stoichiometric nitride is expected because of the excess silicon in the film [12].

The quality of the nitride seal was tested as follows. First, the low-bias I–V curves of a sealed device were measured inside a vacuum system at both atmospheric pressure and at 5 μT. Then the silicon-nitride window was punctured using a fine probe, and the measurements were repeated. Figure 8 shows the I–V curves for both the sealed and punctured devices. For the sealed microlamps (data points (a) and (b)), there is no dependence in the I–V curves on vacuum-pressure. For the punctured devices, however, the characteristic (data points (c) and (d)) are strongly dependent on vacuum-pressure. The similarity in the dependence of data points (a), (b), and (d) indicates that the background pressure in the sealed devices is a good vacuum.

Figure 9 shows the electrical characteristics of a microlamp device with a polysilicon filament 350 μm long and 5 μm wide. Initially, the device resistance increases since polysilicon has a positive TCR. At higher bias, there is a kink point P where the resistance actually decreases. Guckel et al. observed a similar behavior [3] and suggested that at this point the polysilicon filament is heated sufficiently to cause thermal breakdown [13]. For voltages higher than those at point P in Fig. 9, the electrical characteristics are irreversible, and we typically do not operate in this region. We are presently carrying out further experiments at the high-voltage range.

Figure 10 shows the optical power of a microlamp as a function of the applied bias measured with an optical pyroelectric detector. The point P corresponds to the kink in the I–V characteristic. The radiated power emitted by the incandescent filament is in the order of μW and clearly visible to the naked eye. The power needed to reach visible incandescence is approximately 5 mW for a 510 × 5 × 1 μm³ device.

We have measured the time for the filament to cool down from its temperature at incandescence to room temperature. This time, easily observed by monitoring the near-zero-bias resistance after power is removed from the lamp [14], depends on the filament length and is typically several ms (for the full transient) for microlamps exceeding 300 μm in length.

![Optical Transmittance](image)

**Fig. 7.** Measured optical transmission spectrum for a 1.3 μm-thick low-stress silicon-nitride membrane.

![I–V Curves](image)

**Fig. 8.** Microlamp I–V curves: for a sealed microlamp: (a) in a pumped vacuum chamber at 1 atm, (b) in a pumped vacuum chamber at 5 μT; for a punctured microlamp: (c) in a pumped vacuum chamber at 1 atm, (d) in a pumped vacuum chamber at 5 μT.

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Although demonstrated for the purpose of building a microlamp, the fabrication sequence described here can also be used to provide a microvacuum housing for other structures on a silicon substrate.

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References