Microchopper-Modulated IR Microlamp

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ABSTRACT

We describe the design, fabrication, and operation of a chopped microincandescent IR source which can be used in applications demanding a modulated IR output at a fairly high frequency (typically above 1kHz). Such a source is typically required to reduce background noise and to improve signal amplification. The chopper and source are formed primarily using surface micromachining in a continuous batch process to produce a microencapsulated polysilicon filament IR source similar to that described by Mastrangelo and Muller [1] and an overlying shutter based upon the resonator structures first introduced by Tang and Howe [2]. Although Tabata et al [3] have used bulk micromachining to produce a resonating comb-drive shutter to chop IR entering a detector, this research is the first to combine fabrication of an IR source and chopper and to make extensive use of surface micromachining. Experimental choppers were operated between 9 and 15 kHz.

A nine-mask process produced the shuttered microlamp. Six of the masks were used to fabricate the incandescent source and the remaining three produced the shutter positioned above it. The six-mask microlamp process is slightly modified from that of Mastrangelo [1]. Aside from layout changes, the new process replaces a potassium hydroxide etch with a nitric acid/hydrofluoric-acid mixture to form a trench below the filament in the substrate and it uses *n*-type dopants for the filament. Post-fabrication tests and measurements show that device yield is approximately 98% for the microlamp. Yields for the shutter processing were above 80% when 3-micrometer features were employed, but dropped to about 50% when 1-micrometer features were used. Although radiative output peaks in the IR, visible output radiation, becoming quite intense at higher filament voltages, was clearly observable during microlamp testing even under normal indoor illumination as will be shown in a video. To avoid polysilicon recrystallization that would permanently change the filament resistance, the drive voltage must be kept below a "reversible" region that can be found by characterizing the ***I-V*** characteristic of the microlamp. When the applied voltage is held below the recrystallization voltage, the microlamp operates for over four hours with less than 10% change in its current.

The measured shutter resonant frequencies matched closely those obtained through simulations. We designed a total of 81 different shutters having resonant frequencies from 1 to 10kHz. Deviations between the measured and calculated resonant values were smaller than 2%. In contrast, the measured bandwidths (~200Hz), were an order-of-magnitude smaller than the calculated bandwidths (~2kHz). In addition, measured displacements ranging from 1 to 10um were larger, also by an order-of-magnitude, than simulated expectations. The matches in resonant frequencies, combined with the mismatches in bandwidths and displacements, suggest that the damping effect modeled in simulation has been overestimated. The polysilicon shutters were found to absorb most of the visible output radiation although an infrared-absorbing metal layer would be needed in order to extinguish completely all IR output.

INTRODUCTION

Since their introduction in the work of Tang and Howe [2], resonant polycrystalline-silicon microflexures, driven by electrostatic comb structures, have proven themselves as reliable frequency standards [4]. With design modifications, these microstructures can also function as micro-chopping elements that can be produced compatibly with electronic components to function as key elements in a number of special-purpose MEMS. An early example is the miniaturized electrostatic voltmeter or "field mill" described by Hsu and Muller [5] which was later improved by Loconto and Muller [6]. The microchopper in the "field mill" interrupts an electric field which gives rise to currents in a detector electrode that are proportional to the difference in voltage between a test surface and the detection electrode. Choppers are also key components for photoemissive and photosensing systems where they can be used as shutters to chop the optical signals and enable phase-locked system designs. By making such systems suitable for MEMS, microchoppers open important new engineering applications.

Mastrangelo [1] has introduced a

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microincandescent source that is suitable as a very tiny infrared emitter. Its construction can be combined, using surface micromachining, with the resonant-shutter technology to produce a microshuttered IR source. The source may have applications in sensors, remote controls and communications, and as nonlinear components in circuits that operate under hostile environments .

DESIGN and FABRICATION

The microlamp has a similar design to that of Mastrangelo [1] and consists of two main elements: a suspended *microbridge* filament that is anchored at both ends, and a *microshell* that hermetically seals the filament under low pressure. The filament is made of polycrystalline silicon coated with a layer of silicon nitride. Another layer of silicon nitride acts as the window material. Mastrangelo measured a radiant power of ~ 300 microwatts peaked strongly in the infrared with a filament power of 5 mW [7]. The sources produced in this work are noticeably brighter although measurements of brightness have not been carried out as yet.

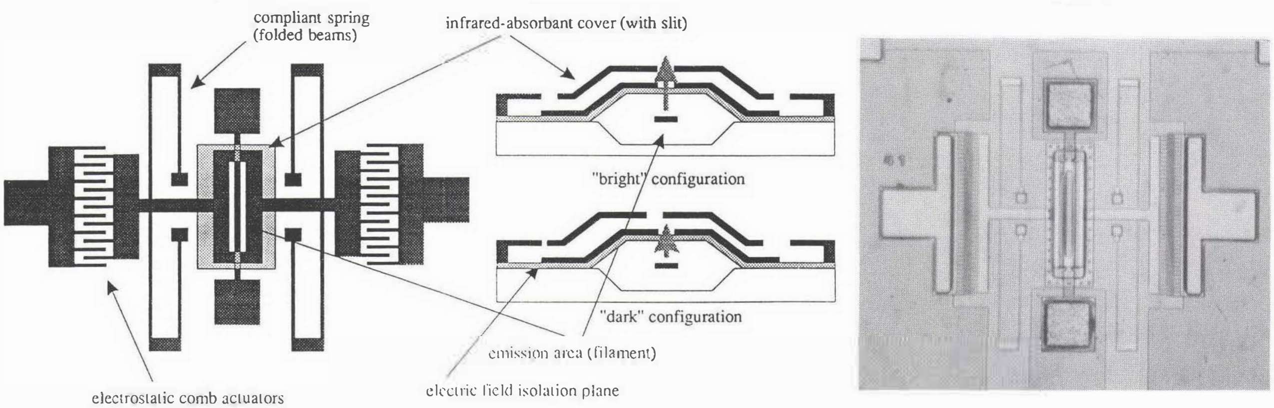

Figure 1. *Layout, cross section, and die photograph of a microchopped IR source. The microlamps are 100μm by 300 μm and the overall width of the assembly is 1.05 mm.*

Figure 1 shows a layout, cross section and die photograph of the microchopper IR source. The fabrication process for it uses eleven layers and nine masks. The microlamp is formed in seven layers and six masks, while the shutter is built in the remaining four layers and three masks. Figure 2 provides a processing summary. The process uses a *p*-type, <100> silicon wafer as substrate and begins with the deposition of 500 nm of low-stress silicon nitride on it. This layer of nitride forms the bottom half of the coat that protects the polysilicon filament. The undoped filament is 1um thick. A

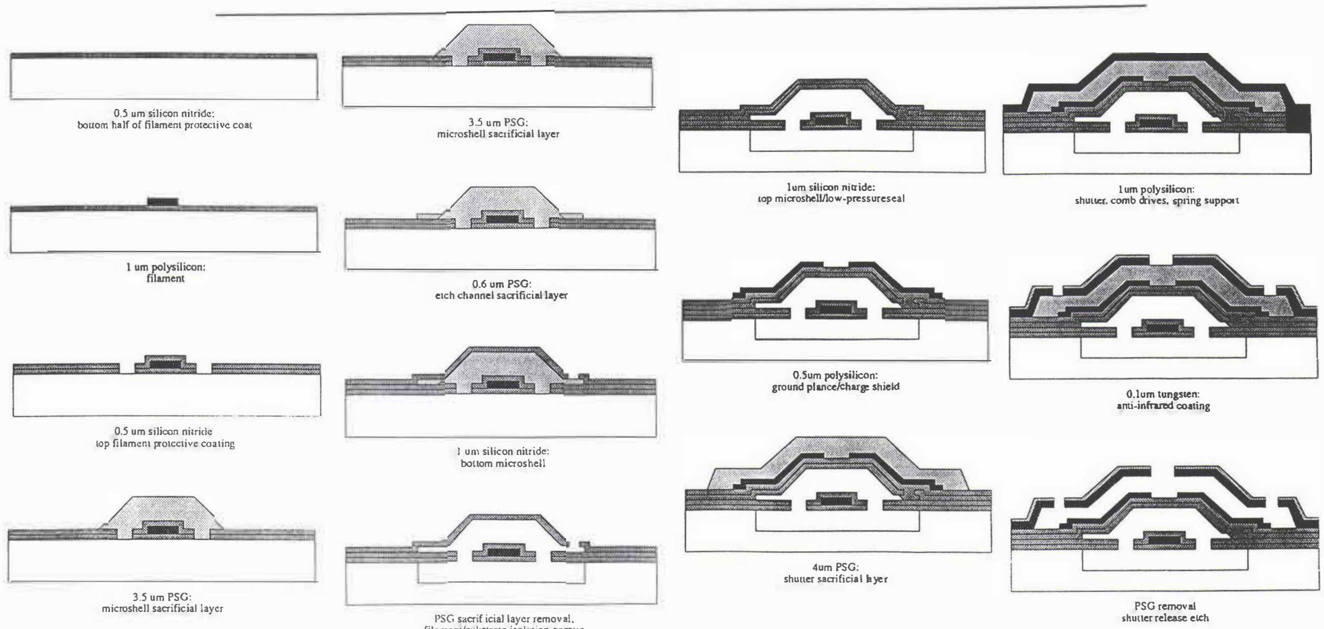

Figure 2. *Processing steps for thc microchopped IR source.*

phosphorus-rich silicon dioxide layer (PSG) is then deposited above the filament, and from it phosphorus is driven into the filament in a two-hour, 1050C anneal. The PSG layer is then removed and a 500nm silicon nitride deposition above the filament completes the filament protective coating. The two silicon nitride layers are patterned and etched, near the filament, to provide an opening to the substrate. Silicon etchant used in subsequent steps opens an isolation groove under the filament.

A thick PSG sacrificial layer, for the microshell, is followed immediately by a thin PSG layer for the etch channels. The silicon nitride microshell is next deposited, in two 1µm depositions. Etch channels are defined above the thin PSG after the first 1µm deposition. The wafer then undergoes a long 5:1 BHF immersion, during which the BHF attacks and removes the PSG sacrificial layers enclosed in the shell. Another immersion step, in a VLSI silicon etchant (consisting of, 50:20:1 HNO_3:H_2O:HF by weight) follows the BHF dip to form the underlying isolation groove. Since this silicon etchant is isotropic, prolonged immersion undercuts the substrate below the filament so that a cavity is formed in which the filament is suspended. The second 1µm silicon nitride deposition forms the top half of the microshell and hermetically seals the microshell at ~300mtorr, the LPCVD deposition pressure for low-stress silicon nitride. A silicon nitride etch, not shown in the figure, opens the filament contact and completes the improved microlamp process.

A 500nm undoped polysilicon layer is then deposited and patterned. It will act as the charge-shielding ground plane. The sacrificial PSG layer for the top shutter, 4µm-thick, follows the ground-plane deposition and shutter-support anchors to the substrate are defined in this step. The final polysilicon layer, 1µm thick, constitutes the shutter and the actuator. The two polysilicon layers are doped during a high-temperature anneal that drives the dopant from the PSG sacrificial layer into the polysilicon. To ensure doping symmetry, another PSG layer is deposited above the polysilicon to act as the upper dopant source for the shutter. A thin tungsten coat (100nm) is sputtered above the polysilicon shutter and the two layers are patterned in one step. Wet-etching the wafer in 5:1 BHF removes the PSG and frees the shutter.

Eighty-one shuttered microlamps, of varying component sizes, were designed using the KIC layout generator. Variations include three filament sizes (widths of 4, 10, and 20µm), different electrostatic comb sizes (1, 2, and 3µm), comb gaps (1, 2, and 3µm), and compliant supports of varying widths (1, 2, 3µm).

MEASUREMENTS and CHARACTERIZATION

Only those microlamps with 10µm-wide filaments were tested for yield. Of 324 microlamps tested in the 12 central dice of the wafer, all but four survived the 6-mask process and are functional (two of the four "dead" microlamps had broken microshells, while the other two had broken filaments). Consequently, the 6-mask microlamp process yielded 98.8% .The lamps were surprisingly robust; all 320 were operational after the shutters were fabricated. Fabricating the shutter (3-mask process) was more difficult than fabricating the microlamp, primarily due to difficulty in the final release etch. Because of their large surface areas and relatively fragile beam supports, many shutters were torn from their anchors during rinsing. Even though precautions were taken to insure minimal rinse-deionized-water flow, approximately 50% of the shutters were lost. We believe that significant yield improvement would follow the use of the supercritical drying technique described by Mulhern et al [8].

Figure 3 is a plot of microlamp lifetime measurements as performed on the HP4145B. The lifetime values were obtained by applying a constant voltage across the filament until the current across the filament changed by more than 10% of its normalized value. Each data point is the average of three

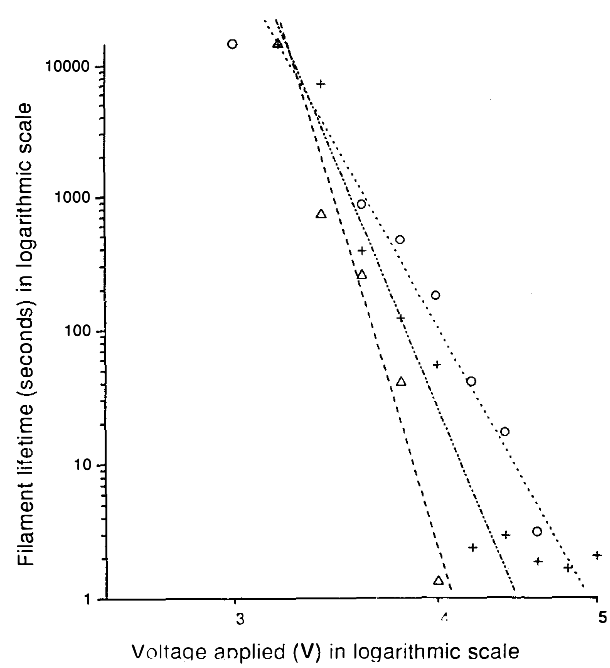

Figure 3. Measured lifetimes of micro-IR sources as a function of voltage drive. Lifetime terminated if current changes by greater than 10% of nominal value. Plotted values are averages of 3. Filament widths: 4 µm o, 10 µm △, 20µm +.

measurements. Due to time constraints on equipment usage, lifetime measurements at the lowest voltage were stopped after 4 hours for all filament widths, which is why the extrapolated lines for these measurements seem to converge at approximately 4 hours. However, at low voltages (~ 3 volts), the filament resistance changes very little for all microlamps, and we expect them to last much longer than 4 hours. The log voltage vs. lifetime plot for the polysilicon filament consists of only one line with a single slope, suggesting that a single mechanism dominates the filament-degradation process, most likely polysilicon evaporation.

Eleven of the 27 shutter designs survived the release etch and were operational. Of the 27 shutters designed for the 10um-wide filament, most of the 9 designs that use 1µm-wide folded beams did not survive the release etching and rinsing. Those that were fabricated could not be powered without a failure caused by the overly flexible driver combs becoming stuck to the substrate. In fact, we found that thin beams and small gap spacings led to failures in all 1 µm-gap beams whereas nearly 100% of the 2 µm-gap shutters were functional.

For the 11 shutter designs that operated, the resonant frequencies match very closely to predicted values [9]; deviations from theory are less than 5%. Such close matches in resonant frequencies suggest that modeling of the folded-beam spring constants and the shutter mass used in the simulation is very accurate. However, the observed bandwidths for all these shutters (approximately 200Hz) are much lower than those obtained by simulation, implying that the simulation may overestimate shutter damping . The narrow bandwidth makes it necessary to tune very carefully in order to drive these microchoppers at their resonant peak. The largest displacement measured was 30µm (peak-to-peak) at 10.25 kHz.

CONCLUSIONS

The design, fabrication, and operation of a micro-chopped luminous source has been demonstrated for the first time. Both a vacuum-encapsulated source and an overlying resonant polysilicon microflexure chopper have been produced in a nine-mask continuous batch-fabrication process. Yields of nearly 100% were achieved in the first steps of the process which produced the encapsulated IR sources. The silicon nitride-windowed microcavities proved adequately robust for further steps needed to fabricate the resonant microchoppers. The critical release-etch step was successful for shutters having feature sizes above 2µm, but generally failed for 1µm features. Additional failures of greater than 50% of the shutters were experienced in the final-rinse step. The measured resonant frequencies for the completed microchoppers agree well with the predictions of simulations, indicating accurate modelling of the folded beams and shutter masses. The simulation, however, substantially underestimates the measured mechanical quality factor and the maximum shutter displacement. Both inaccuracies are thought to result from improperly modeling damping in the system. Several design changes leading to more simplified processing and improved performance have become evident in carrying out this research. These changes, which will reduce the mask count and modify the shutter design, should move the microchopped IR source closer to system applications.

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