High-resolution micromachined interferometric accelerometer

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We demonstrate a promising type of microfabricated accelerometer that is based on the optical interferometer. The interferometer consists of surface-micromachined interdigital fingers that are alternately attached to a proof mass and support substrate. Illuminating the fingers with coherent light generates a series of diffracted optical beams. Subangstrom displacements between the proof mass and frame are detected by measuring the intensity of a diffracted beam. The structure is fabricated with a two-mask silicon process and detected with a standard laser diode and photodetector. We estimate that the minimum detectable acceleration is six orders of magnitude below the acceleration of gravity, i.e., 2 $\mu g/\sqrt{\mathrm{Hz}}$ in a 1 Hz bandwidth centered at 650 Hz. © *2000 American Institute of Physics.* [S0003-6951(00)02122-7]

Accelerometers for applications such as navigation, seismology, and acoustic sensing are often required to detect accelerations below a micro-g. In order to achieve such resolution, it is necessary to detect subangstrom displacements of a suspended proof mass with a mechanical resonance below a kilohertz. For some applications, the system must be packaged in volumes less than 10 cm^3.

In one experiment, an optical interferometer is used to measure subangstrom displacements of a mirror that is mounted to a suspended proof mass.[1] A neodymium-doped yttrium–aluminum–garnet (Nd:YAG) laser is frequency locked to a Fabry–Pérot accelerations in the hundreds of pico-g can be detected, the system is difficult to miniaturize and package in small volumes.

A variety of microfabricated accelerometers containing surface-micromachined proof masses with piezoresistive, piezoelectric, or capacitive transducers address the packaging requirements but generally lack micro-g resolution. However, Kenny and co-workers have achieved micro-g resolution and centimeter-scale miniaturization by combining a bulk-machined proof mass with the electron tunneling displacement sensor.[2,3] This is accomplished by bonding the bulk-machined proof mass and support substrate to a die containing a cantilever with a tunneling tip and electrodes for controlling the spacing between the tip and proof mass. Similar to scanning tunneling microscopy, feedback control circuitry is used to keep a constant tip-to-proof mass spacing of 10 Å. In other work, a surface-micromachined tunneling accelerometer fabricated by a single-mask process was demonstrated to have a resolution of 20 $\mu g/\sqrt{\mathrm{Hz}}$ at 100 Hz.[4]

We report here a type of microfabricated accelerometer that combines a bulk-machined proof mass and support substrate with an optical interferometer. The interferometer consists of interleaved fingers that are attached alternately to the proof mass and support substrate. The interdigital system forms an optical diffraction grating where the displacement of the proof mass relative to the support substrate is measured with a standard laser diode and photodetector. In our arrangement, the positioning of the laser diode and photodetector is not critical since both optically reflective surfaces of the interferometer are integrated onto the same device. The interdigital sensing technique, initially developed for the atomic-force microscope, is capable of detecting displacements of less than 10^{-3} Å/$\sqrt{\mathrm{Hz}}$ at 650 Hz.[5] In this letter, we demonstrate that the interdigital sensor can detect accelerations on the order of 2 $\mu g/\sqrt{\mathrm{Hz}}$ at 650 Hz. We anticipate that external feedback circuitry may not be necessary since the interdigital sensor is linear over displacements on the order of 100 Å.

A schematic of the interdigital accelerometer is shown in Fig. 1. The proof mass, which contains a set of extending fingers, is attached to the support substrate by a flexible cantilever. Alternating fingers extending from the support substrate complete the diffraction grating. When the grating is illuminated, the light is diffracted into a series of optical beams. In the far field, the spacing between the beams is approximately $2h\lambda/d$, where h is the separation between the grating and photodiode, d is the grating pitch, and λ is the wavelength of illumination. The intensity of the zeroth-order beam varies as $\cos^2(2\pi z/\lambda)$, where z is the displacement of the proof mass with respect to the support substrate. For our devices, $\lambda = 635$ nm, $d = 6$ μm, and h is typically a few centimeters. This provides spacing of a few millimeters between the diffracted spots.

The accelerometer was fabricated with a two-mask process. The starting material was a 500-μm-thick, double-side polished, ⟨100⟩ silicon wafer. First, the thickness of the interdigital fingers and the cantilever support was defined with a deep reactive ion etch (DRIE). We typically chose etch

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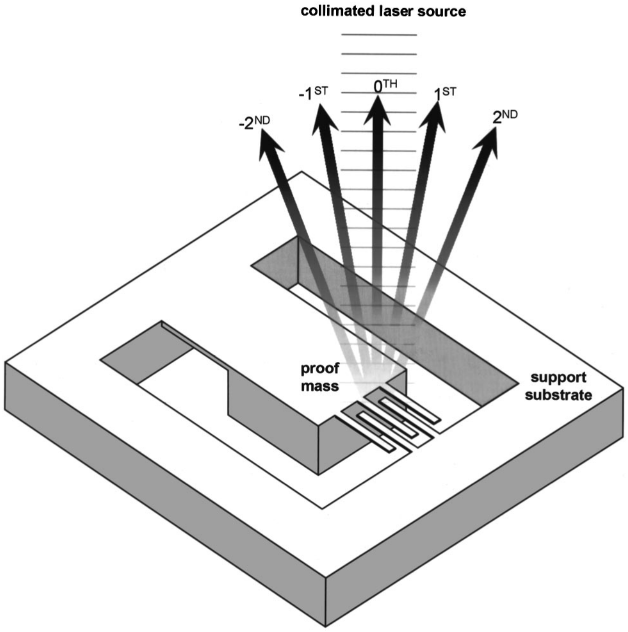

FIG. 1. Device geometry and detection. An incident coherent beam is diffracted off the reflective surfaces of interleaved fingers, which are alternately attached to a cantilevered proof mass and the support substrate. The displacement of the proof mass relative to the supporting frame determines the intensities of the diffracted orders. The intensity of a low-order beam is detected with a silicon photodiode. The fingers sizing is greatly exaggerated in this schematic; fingers are defined in the process to be the same thickness as the cantilever supporting the proof mass and have a 10:1 aspect ratio.

depths between 15 and 30 μm. The frontside pattern was protected with a thick layer of photoresist and mounted to a quartz carrier wafer. A second DRIE was then used to define and release the proof mass from the backside. The device wafer was dismounted from the carrier wafer with an overnight soak in acetone and subsequently rinsed in methanol, 2-propanol, and water. An optical micrograph of the final device is shown in Fig. 2.

Since the process did not include a buried etch stop, the backside etch was timed and individual devices were protected with photoresist once the proof mass was released. While most of the devices survived the release, induced stress between the device wafer and carrier cracked the interdigital beams on the majority of the devices. We anticipate that the process can be improved by adding a buried etch stop and eliminating the carrier wafer.

The acceleration resolution was measured by oscillating the device with a piezoelectric actuator. The diffraction grating was illuminated with a collimated laser diode ($\sim$1 mW at a 635 nm wavelength) and the intensity of the diffracted mode was measured with a silicon photodiode. The photodiode current was converted to a voltage with a 10 kΩ resistor, amplified, and connected to a spectrum analyzer. Since we did not isolate the accelerometer from external vibration, the noise spectrum revealed disturbances from the mechanical mount and our environment. In order to estimate the resolution of the actual device, we chose to modulate the piezoelectric actuator at a frequency where the background noise was a minimum. This was typically between 600 and 700 Hz. Figure 3 shows the response of the photodiode when the actuator was driven by a 650 Hz sine wave with a 10 mV peak-to-peak amplitude. This corresponds to a 1 Å displace-

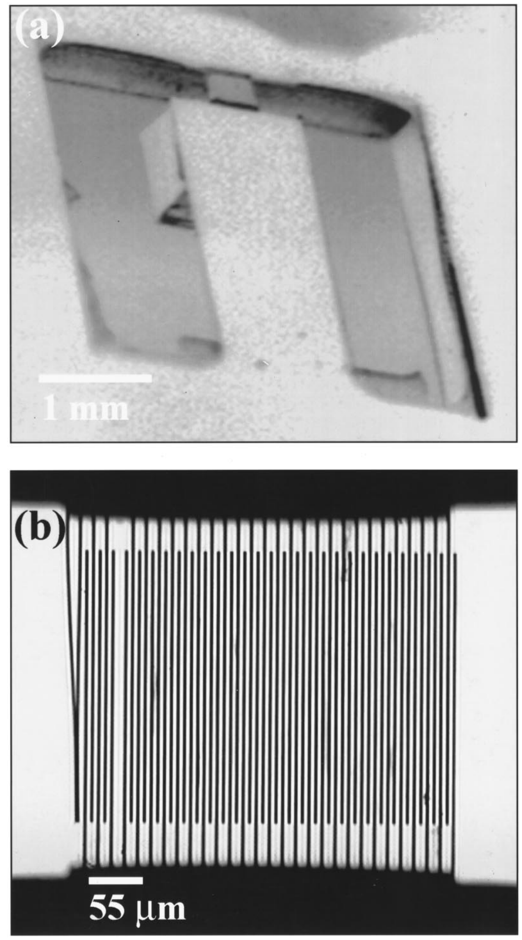

FIG. 2. (a) Optical micrograph of the accelerometer. The support cantilever is 2100 μm$\times$1000 μm$\times$20 μm; proof mass is 1000 μm$\times$1000 μm$\times$500 μm. (b) Optical image of the diffraction grating. The beams are approximately 2 μm wide at a 6 μm pitch. Fingers tangled or stuck together after dismount were manually separated or broken off with the aid of a probe station. Two peripheral fingers remain stuck, but do not interfere with the optical response of the device. From the measured mechanical resonance of 906 Hz, we calculate that the cantilever thickness is approximately 20 μm and the effective spring constant is 40 N/m.

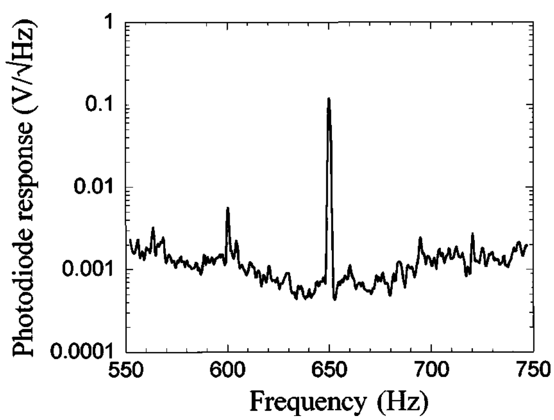

FIG. 3. Frequency response of the accelerometer to an acceleration of 170 μg at 650 Hz. The voltage response of the photodiode shows the intensity of the first-order diffraction beam. The acceleration was driven by a piezoactuator excited by a 10 mV peak-to-peak sinusoidal input, corresponding to a displacement of approximately 1 Å.

ment amplitude of the device, and a 170 μg acceleration. At this frequency, the signal-to-noise ratio is approximately 100:1, indicating a noise level resolution of 1.7 $\mu\mathrm{g}/\sqrt{\mathrm{Hz}}$. Several similar measurements were made in the frequency range between 600 and 700 Hz, resulting in comparable resolution. Figure 3 is representative of the device response in this range of frequencies where environmental noise was minimized in our experimental setup.

The equivalent acceleration from thermal mechanical noise of the device is equal to $\sqrt{4k_bT\omega_0/m_pQ}$ where k_b is Boltzman's constant, T is temperature, m_p is the proof mass, ω_0 is the resonant frequency of the cantilevered proof mass, and Q is the mechanical quality factor.[6] Our device has a resonance of 906 Hz, a proof mass of 1.2 mg, and a Q of 90. For this device, the thermal noise source is expected to be 90 $\mathrm{ng}/\sqrt{\mathrm{Hz}}$, indicating that our device is limited by detected and environmental noise sources.

The interdigital accelerometer demonstrates a measurement technique that achieves resolution comparable to that of the tunneling accelerometer. Our device is fabricated with a two-mask process and requires no feedback control circuitry. The design is well suited for fabrication of arrays where resolution might be further improved through differential measurements. The small size of the microfabricated structure and the simplicity of the optical detection scheme show promise towards small-volume packaging. For instance, our grating pitch of 6 μm with an illumination wavelength $\lambda = 635$ nm allows a minimum optical path length of about 1 mm to the detector. We envision a packaging scheme where the illumination source and photodetector can be either fabricated as a unit, or surface mounted on a circuit board such that they can be aligned within close proximity to the mechanical accelerometer demonstrated here, allowing packaging within a 10 cm^3 volume.

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