Monolithic Microbridges in Silicon Using Laser Machining and Anisotropic Etching

M. Alavi, Th. Fabula, A. Schumacher and H.-J. Wagner

Institut für Mikro- und Informationstechnik
der Hahn-Schickard-Gesellschaft für angewandte Forschung e. V.
Wilhelm-Schickard-Straße 10
W-7730 Villingen-Schwenningen, F.R.G.

Contribution to "EUROSENSORS VI", San Sebastian, 5.-7. October 1992,
accepted for publication in Sensors and Actuators

Introduction

Resonant sensors have several advantages in the field of precision measurement technique because of their high sensitivity, high resolution and semi-digital output. These structures can be realized in silicon by means of photolithography and anisotropic etching [1].
Several criteria have to be considered in designing microresonators for sensor applications (i.e. force, pressure, temperature) like shift of the resonance frequency due to change of the stress state in the resonator, excitation and detection of specific vibration modes and the mechanical quality factor. For application as force sensor the microresonator of the sensor device has usually the form of a vibrating beam clamped at both ends. These microbridges are monolithically fabricated by anisotropic etching of silicon doped with high concentrations of additives to achieve an etch stop. However, the thickness of the doped beams is limited to few microns due to the specific doping technique. Undoped microbridges with higher thickness can be formed non-monolithically by bonding of two separate silicon structures including the vibrating beam and the supporting pillars [2]. With this method the bonding of small beams seems to be quite sophisticated for fabrication in batch processes. Another conventional technology to produce monolithic microbridges is backside-etching the silicon wafer to the desired thickness followed by separation (wet anisotropic etching or plasma etching techniques) of the vibrating elements. Although this method yields remarkable results [3] the wafer has to be photolithographically patterned on both sides and therefore

beam-on-diaphragm structures [4] cannot be realized. This paper presents a method for the fabrication of monolithic microbridges in silicon with a thickness up to 200 μm by combination of laser machining and wet anisotropic etching. In contrast to the conventional technologies mentioned above this new method allows the fabrication of monolithic beam-on-diaphragm structures for sensor applications with triangular microbridges as resonating elements.

Principle of the method

The combination of laser machining and anisotropic etching of single crystal silicon leads to a fabrication of new types of microstructures [5]. The details of the processing method and the experimental setup are described elsewhere [6].
The absorbed energy of the laser beam causes a local temperature rise leading to a melting and/or evaporation of silicon accompanied by a local destruction of {111} crystal planes in a defined region around the molten zones. If these zones are extended along the $[1\bar{1}0]$ direction for a <110> oriented silicon wafer, the following anisotropic etching provides microchannels which are limited by the undamaged {111} planes determinated by the masking layer.

We already applied this method in our laboratory for the fabrication of microchannels with high aspect ratios in <110> silicon wafers [7] and also in <111> oriented silicon wafers [8]. The partially closed forms of the microchannels ("bottle neck") in <110> and <100> silicon with an aspect ratio depending on the parameters of the laser beam are well adapted for this new application of fabricating monolithic microbridges described in this work. If the lateral distance between two neighboring microchannels is less than a certain value determinated by their aspect ratios, microbridges with triangular cross sections can be realized as schematically shown in **Fig. 1** by the example of <110> oriented silicon wafers.

Experimental, Results and Measurements

The experimental setup consists of a cw-pumped Nd:YAG laser system with Q-switch and a computer-controlled xy-table. The pulsed laser beam (wavelength 1064 nm, pulse length 200 ns, pulse frequency 1 kHz, maximum average power 10 W, minimal beam spot size 8 μm) is well suited for silicon micromachining because the photon energy (1.17 eV) exceeds the band gap of silicon (1.12 eV). The laser parameters can be varied to obtain a damaged zone of the desired depth. Three inch <110> silicon wafers (thickness = 380 μm) covered with a thermally grown 1,5 μm SiO_2 layer were used for this investigation. Arrays of microbridges have been produced by photolithographically patterning the SiO_2 layer and precise computer-controlled movement of the silicon wafer along the $[1\bar{1}0]$ respectively [001] direction during the laser machining process. A time-controlled etch process was developed to prevent an over-etching of the microbridges from the convex backside edges. The depth of the damaged zones was set variably up to 300 μm.

The scanning electron micrograph of **Fig. 2** shows an array of triangular microbridges in a <110> silicon wafer after laser treatment in [1$\bar{1}$0] direction, anisotropic etching in KOH solution and removal of the SiO_2 masking layer. The width of the microbridges is 200 μm determinated by the photolithographically patterned masking layer. The SEM micrograph of **Fig. 3** shows the end of a beam in <110> silicon with a thickness of about 30 μm monolithically clamped to the bulk material. The cross-sectional shape of these beams is limited by slow etching {111} crystal planes. It is a triangle with a theoretical slope angle of 35,26° (for further discussion: 35°) to the wafer surface, verified by measured data of fabricated microbridges. Processing the <110> oriented wafers in [001] direction microbridges with an experimentally measured slope angle of 48° (for further discussion: 50°) have been realized as shown in **Fig. 4**. The shape limiting planes are here near {100} planes. The angle of 50° can be theoretically explained by the graphical forecast method of Jaccodine **[9]** based on experimental etch rate data. We fabricated microbridges in various dimensions using different masking patterns, laser parameters and etch steps.

Single crystal silicon is a non-piezoelectric material. The excitation and detection of the resonating element can be realized by piezoelectric thin-film multilayer systems, e.g. ZnO **[10]** or AlN. For an optimal excitation/detection efficiency the relation of the active transducer area on the resonator surface to the cross-sectional area of the resonating beam has to be as large as possible. A comparison of cross-sectional shapes of beams fabricated with angles of

35°, 50° (triangular microbridges) and 55° (prismatic microbridges) is shown in **Fig. 5**.

For testing the dynamic behaviour the triangular microbridges were excited by a piezoelectric ceramic disc and interrogated optically by a laser vibrometer (POLYTEC OFV 1102). This laser vibrometer is based on a fiber optic heterodyne Mach-Zehnder interferometer and comprises a velocity and amplitude demodulator. Using laser Doppler technique the vibrometer evaluates the out-of-plane motions of the reflecting probe. The Doppler-shift of the reflected laser light is measured to generate a real time analogous velocity output signal. An absolute displacement output via counting the interference rings with a resolution of 8 nm is also available. The output signal of the vibrometer is fed to a computer controlled spectrum analyzer (HEWLETT-PACKARD 3588A) with a personal computer as data acquisition system which directly displays the frequency spectrum.
With this method we measured the resonance frequencies of triangular silicon microbridges. The first column of **Table 1** shows the frequencies of a microbridge (α = 35°, length l = 2800 μm, width w = 180 μm and thickness t = 64 μm). The fundamental flexure mode Z1 occurs at 60.9 kHz with a mechanical quality factor of 420 at normal air pressure and room temperature. The deflection amplitude at resonance depends on the efficiency of the piezoceramic excitation. Amplitude values are typical in the nanometer range. **Fig. 6** shows the frequency spectrum of the first three out-of-plane flexure vibration modes (Z1, Z2 and Z3). In order to resolve

the higher vibration modes a velocity spectrum was recorded. The maximum velocity with about 11 mm/s occured at the fundamental mode Z1.

Finite Element Modeling

The primary intention of the Finite Element Analysis in this work is a comparison of microbridges in silicon with triangular and prismatic cross sections with constant width regarding resonant force sensor applications. Due to the slope angles of 35° and 50° and the constant width w = 200 μm the triangular microbridges have thicknesses of 71 μm respectively 120 μm with a beam length of 3000 μm.

To determine the resonance frequencies and the mode shapes of the different silicon microbridges we used a modal analysis. The ANSYS finite element program code offers the Householder and the subspace iteration method for solving the eigenvalue problem **[11]**. Here we used the Householder method with reduced matrices system. The finite element models have about 720 to 1400 3-D isoparametric solid elements (STIF45) with 8 nodes and 300 master degrees of freedom for translation in space. The models are based on the assumption of free, undamped vibrations and an elastic isotropic material behaviour of silicon. For modeling the dynamic behaviour with boundary conditions the microbridges were assumed to be fully clamped on both sides.

Table 1 shows the experimental and numerically calculated resonance frequencies of the different microbridges for the

out-of-plane flexure modes in Z direction, the in-plane flexure modes in Y direction and the first torsional mode (T1). The frequency of the fundamental flexure mode (Z1) depends mainly on the dimensions of the microbridge (length and thickness), the material parameters (Young's modulus, Poisson's ratio) and the boundary conditions. The fundamental resonance frequencies were analytically calculated **[12]** for a fully clamped rectangular silicon beam with a length of 3000 μm and thicknesses of 71 μm respectively 120 μm assuming a value of 1.696×10^{11} Pa for reduced Young's modulus and a material density of 2329 kg/m^3. The results of 69.1 kHz respectively 116.7 kHz are in good agreement with the resonance frequencies Z1 of the prismatic beams in table 1. The mismatch is approximately 1-2 %. The higher vibration modes (harmonics) are normalized to the specific flexure modes Z1 in order to compare the resonance frequencies of the microbridges with different cross-sectional shapes. These values are also listed in table 1 in parenthesises.
Although the results of the finite element calculations are approximative there is good agreement between the experimental values (first column) and the simulated data (next columns).

By utilizing a combined static-dynamic analysis we calculated the force sensitivities to determine the effect of an external axial load. Due to an applied force at the ends of the microbridges a tensile stress will occur in the resonating beams leading to a stress stiffening and therefore to a shift in resonance frequency. A static finite element solution run is applied to determine the displacements and stresses in the microbridges by use of the ANSYS geometric nonlinearity option (stress stiffening). In a subsequent modal analysis the shifts of resonance frequencies are determined. The maximum stress considered in the simulations is the fracture strength of silicon (ca. 200 MPa). The relative change f/f_0 of the fundamental flexure mode Z1 depending on the tensile stress in the microbridge is demonstrated in **Fig. 7**. The highest sensitivity at equal mechanical stress is obtained evidently by the triangular microbridges. Triangular microbridges have about 30-40 % higher sensitivities for an applied load compared to conventional prismatic structures.

Conclusions

A method for the fabrication of triangular shaped monolithic microbridges with thicknesses up to 200 μm by combination of laser machining and following anisotropic etching of photolithographically patterned <110> oriented silicon wafers was presented. Depending on the direction of the laser treatment on the wafer surface, two types of triangular microbridges with an angle of 35° respectively 50° are realized without any use of doping or bonding techniques. Finite element calculations were carried out to determine the resonance frequencies of the microbridges for several vibration modes as well as the sensitivities of these microstructures due to an applied mechanical load. The results give evidence to higher force sensitivity responding to an axial load of the triangular microbridges compared to the prismatic structures produced with conventional processing techniques. These microbridges can therefore be preferentially used as resonating elements of mechanical microsensors with semi-digital output. The batch compatibility of the described method has to be investigated further regarding to thin film technology for piezoelectric excitation/detection of the resonating elements.

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Figure Captions

Fig. 1: Schematic diagram of a triangular microbridge formed by laser machining and anisotropic etching of <110> silicon.

Fig. 2: Array of triangular microbridges in <110> silicon.

Fig. 3: SEM micrograph showing the clamping region of a <110> monolithic triangular microbridge.

Fig. 4: Cross section of a three inch <110> silicon wafer with two opposite monolithic triangular microbridges (slope angles = 50°) after laser machining, anisotropic etching and removing of the masking layer.

Fig. 5: Comparison of cross-sectional shapes of microbridges fabricated by laser machining and anisotropic etching with angle $\alpha = 35°$ **(a)**, laser machining and anisotropic etching with $\alpha = 50°$ **(b)** and conventional etching technology with $\beta = 55°$ **(c)**.

Fig. 6: Optically measured frequency spectrum of the first three out-of-plane flexure modes of a triangular silicon microbridge with a length of 2800 μm, a width of 180 μm and a thickness of 64 μm.

Fig. 7: Comparison of the relative frequency changes f/f_0 of the fundamental flexure mode Z1 due to tensile stress subjected to the silicon microbridge.

Table I: Comparison of experimental measured Z-flexure modes (first column) and numerical computed resonant frequencies for transversal flexure modes (Z1,Z2..,Y1) and the torsional vibration mode T1.

Resonance Frequencies (kHz)					
length	2800 μm	3000 μm			
width	180 μm	200 μm			
thickn.	64 μm (35°)	71 μm (35°)		120 μm (50°)	
mode	experiment	triangle	prisma	triangle	prisma
Z1	60.9 (1.00)	56.6 (1.00)	68.5 (1.00)	94.3 (1.00)	114.1 (1.00)
Z2	168.2 (2.76)	155.5 (2.75)	188,3 (2.75)	258,1 (2.74)	311.5 (2.73)
Z3	327.8 (5.38)	303.9 (5.38)	368.0 (5.37)	501.3 (5.32)	603.9 (5.29)
Z4	536.0 (8.80)	500.6 (8.85)	606.2 (8.85)	819.8 (8.69)	986.9 (8.65)
Z5	749.0 (12.3)	744.8 (13.2)	901.9 (13.2)	1209. (12.8)	1460. (12.8)
Y1	---	136.2 (2.41)	238.8 (3.49)	136.1 (1.44)	274.8 (2.41)
T1	---	595.6 (10.5)	491.0 (7.17)	749.7 (7.95)	634.5 (5.56)

Fig. 1

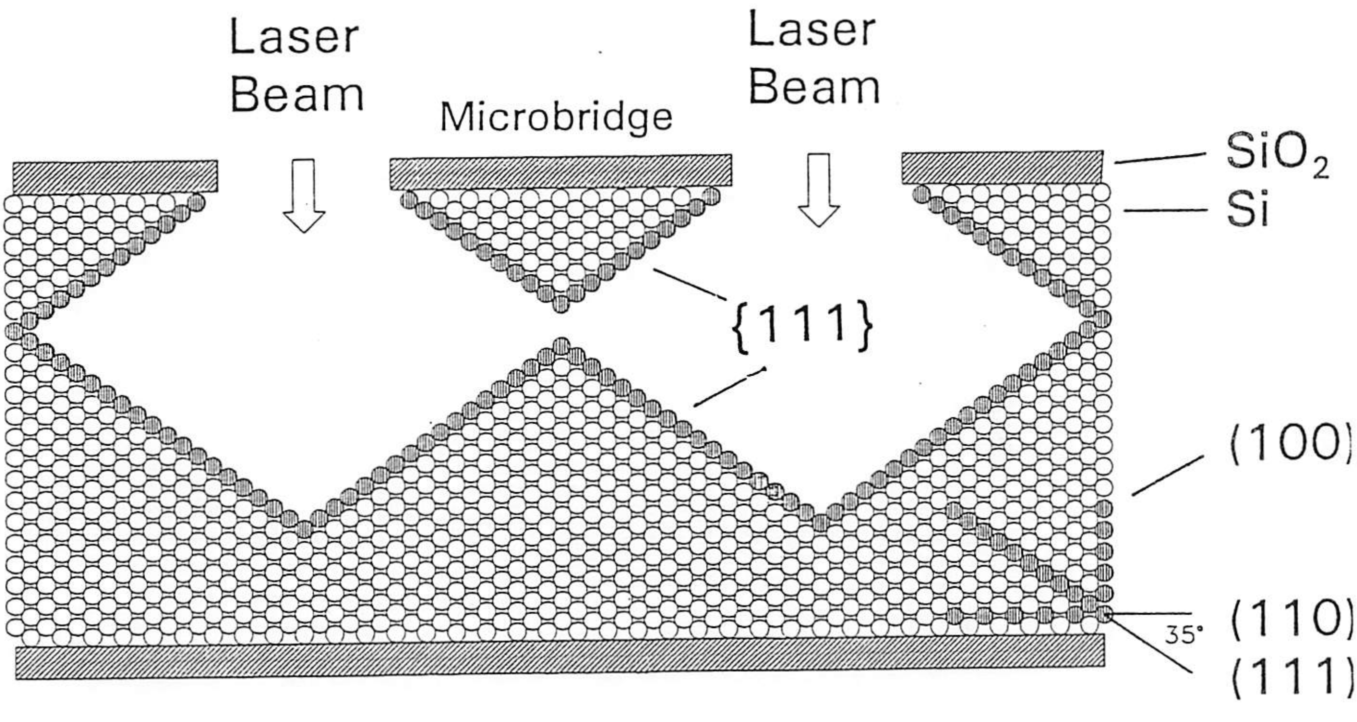

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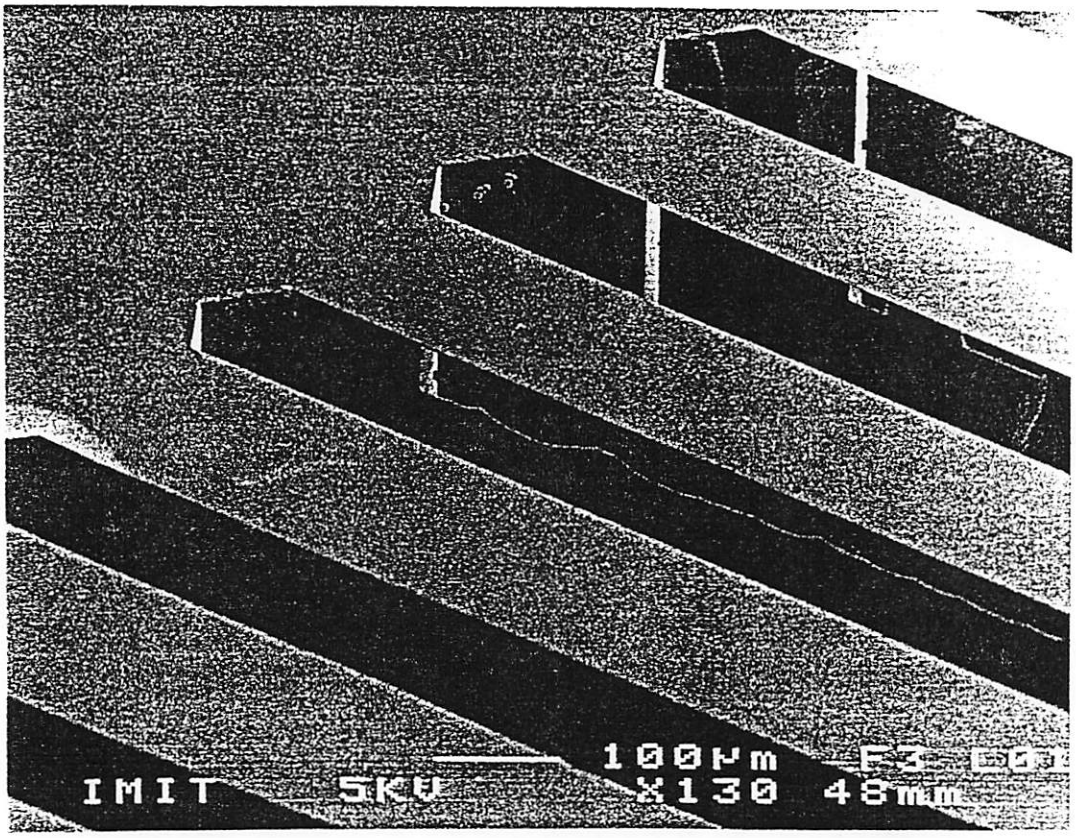
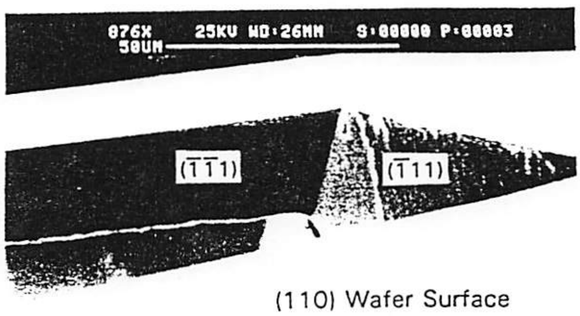
Fig. 2

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$(\bar{1}\bar{1}1)$
$(\bar{1}11)$
(110) Wafer Surface

Fig. 4

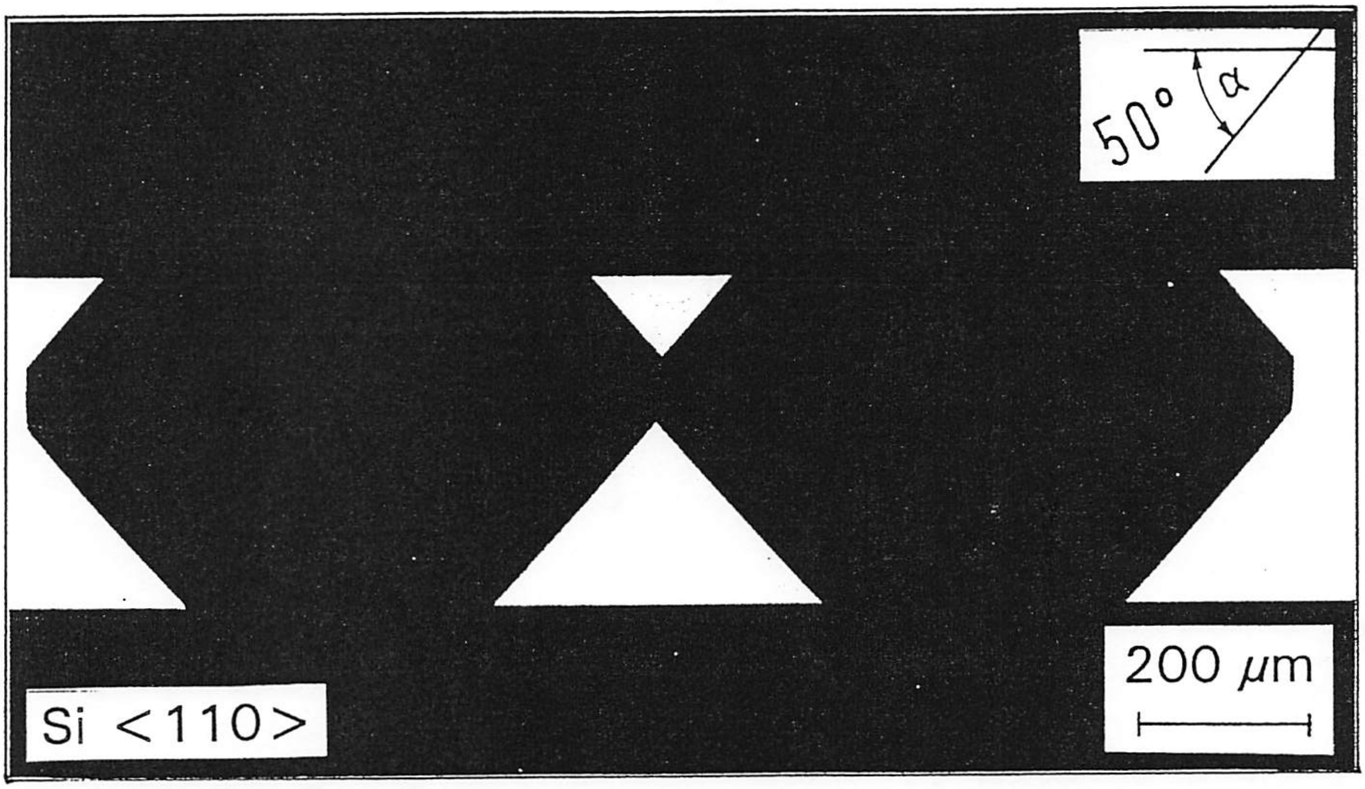
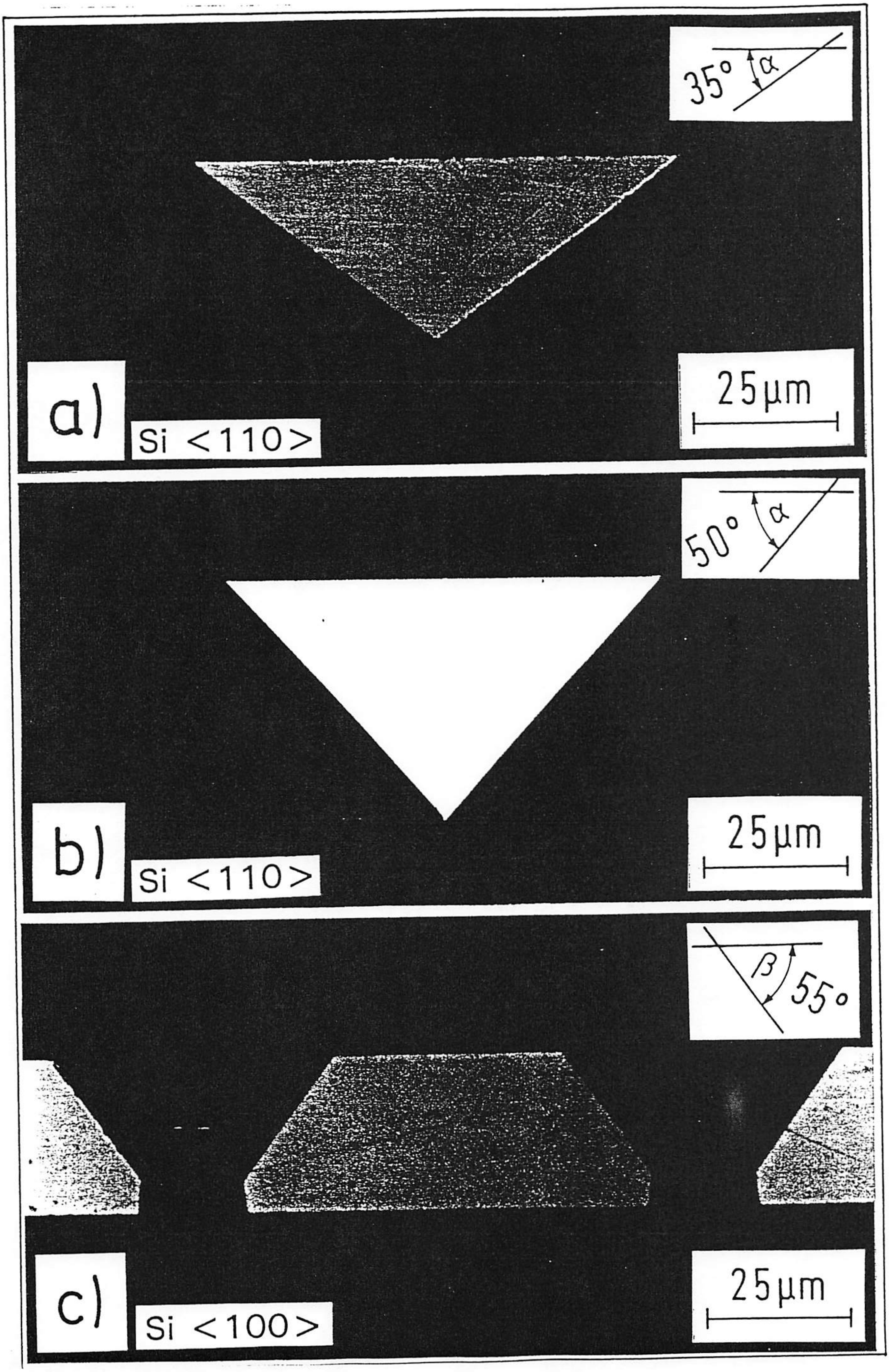


Fig. 5



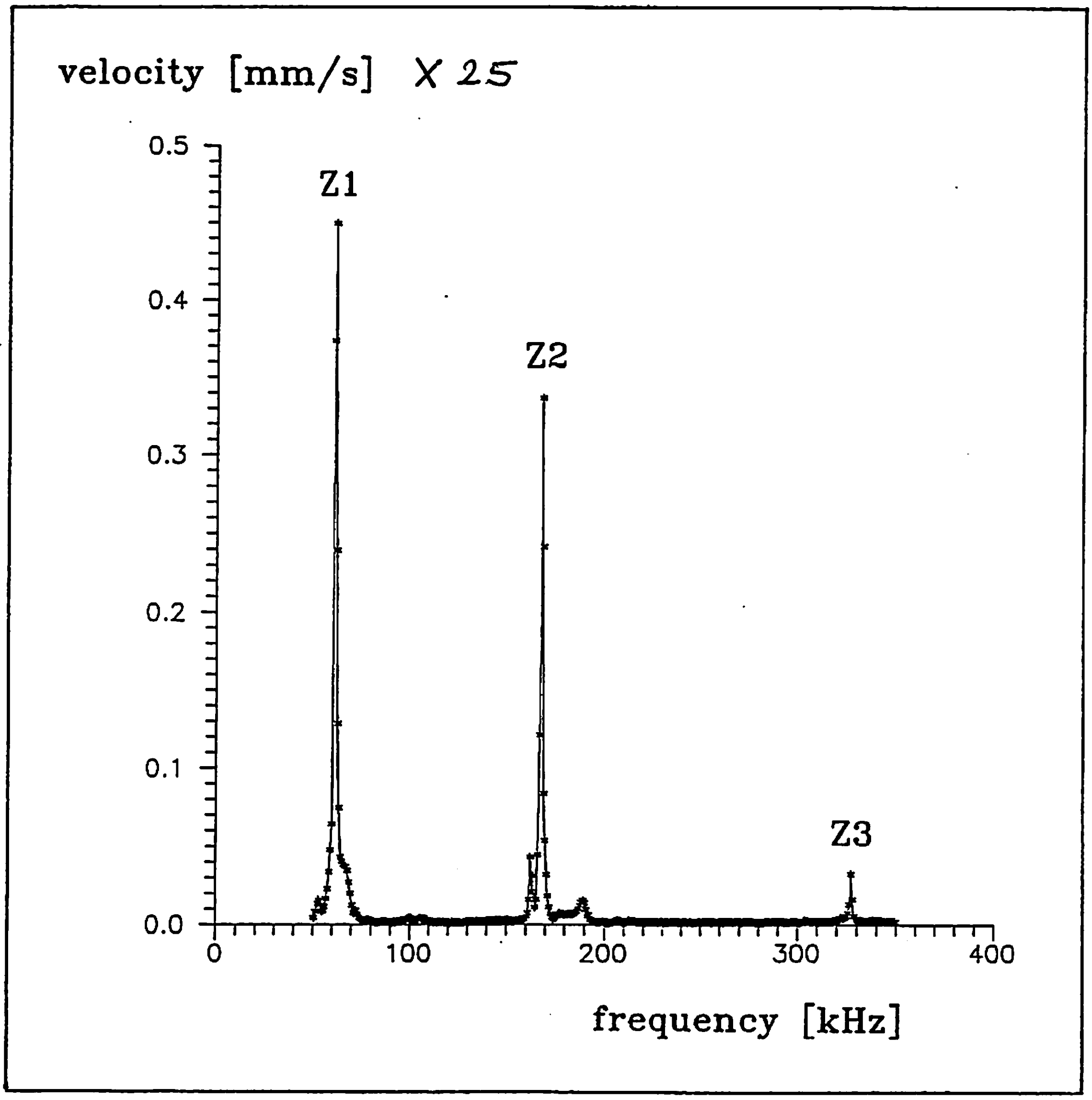

velocity [mm/s] X 25
0.5
0.4
0.3
0.2
0.1
0.0
Z1
Z2
Z3
0
100
200
300
400
frequency [kHz]

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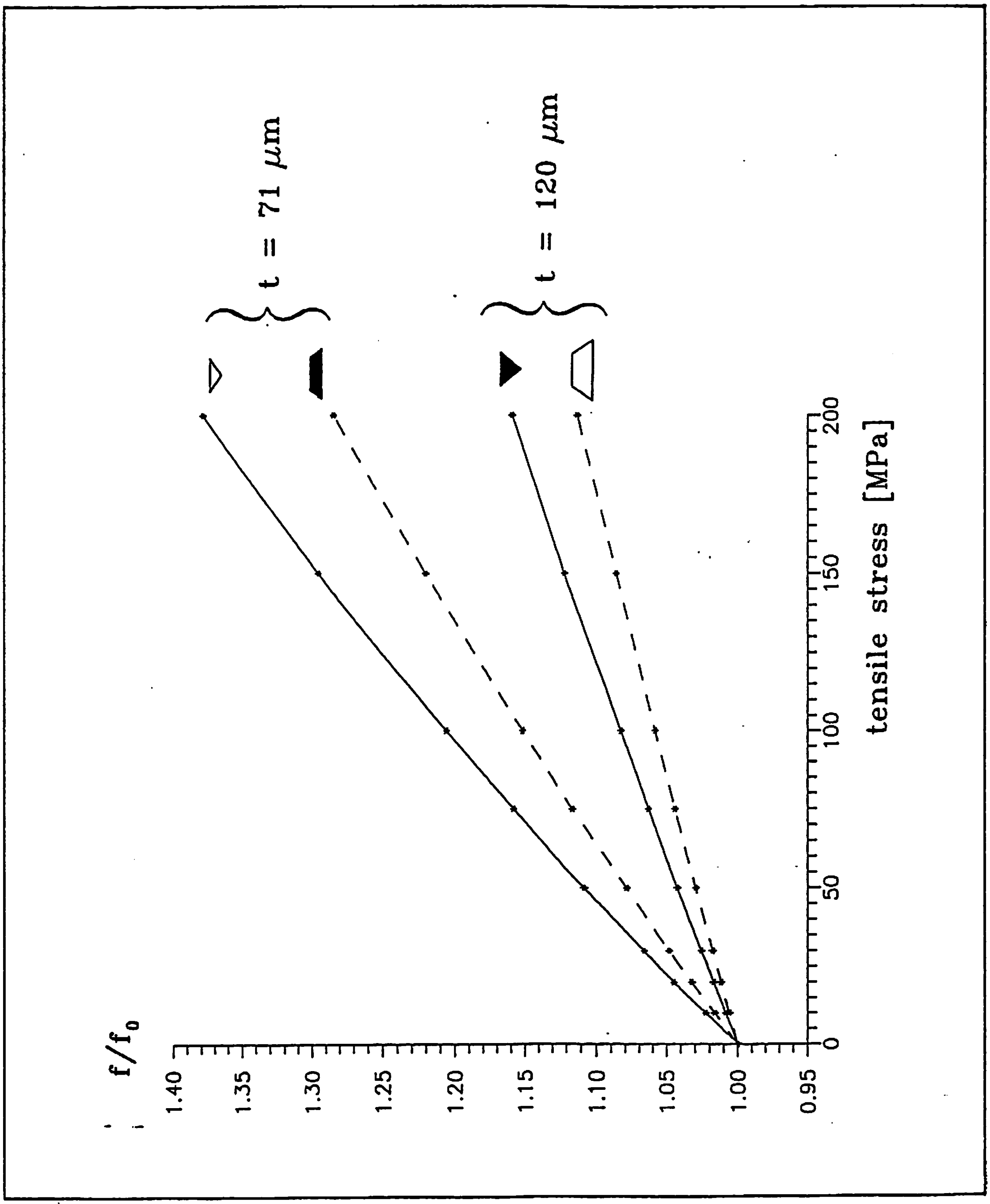
Fig. 7



Abstract:

Microbridges in silicon can be used as resonating elements for the realization of mechanical sensors. These microstructures are usually fabricated by anisotropic etching of silicon doped with (high) concentrations of additives to achieve an etch stop effect. However, the thickness of the doped beams is limited to few microns due to the specific doping technique. Undoped microbridges with higher thickness could be formed by bonding of two separate silicon structures including the vibrating beam and the ribs [1].

This paper presents a method for the fabrication of monolithic microbridges in silicon with a thickness up to 100 μm by a combination of laser machining and wet anisotropic etching. The details of the processing method and the experimental setup are described elsewhere [2]. Typical results of this technique are partially closed microchannels in <110> silicon with an aspect ratio depending on the parameters of the laser beam [3].

If the lateral distance between two neighboring microchannels in a <110> silicon wafer is less than a certain value determined by their aspect ratios, microbridges with triangular cross-sections can be formed by this method as schematically shown in Fig. 1. The SEM micrograph of Fig. 2 shows a monolithic microbridge (thickness $\approx$ 30 μm) in <110> silicon. Microbridges in <100> silicon can also be produced by laser machining and anisotropic etching. The geometry of the microbridges can be dimensioned by the parameters of the masking layer and the laser beam. Finite Element Analysis of static and dynamic behaviour of the triangular microbridges with regard to their application as resonating elements of mechanical sensors are in progress.

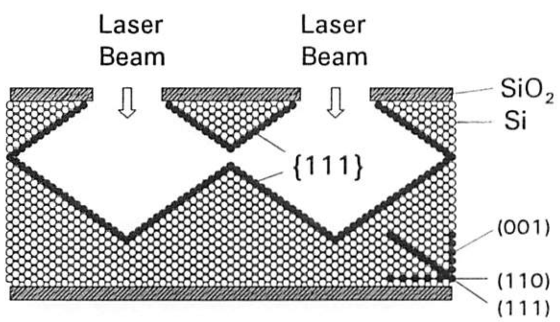


Fig. 1: Schematic diagram of a triangular microbridge formed by laser machining and anisotropic etching of <110> silicon.

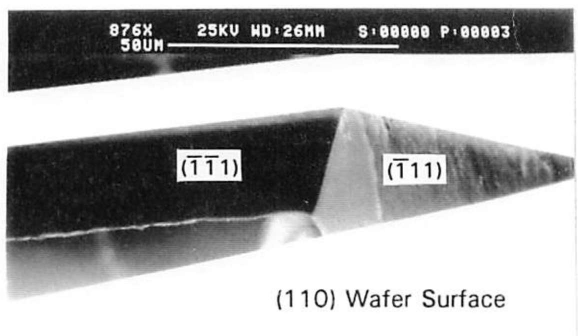


Fig. 2: SEM micrograph of a monolithic triangular microbridge in <110> silicon.

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