Pb(Zr,Ti)O3 on CVD Diamond
A New Material System for MEMS Actuators

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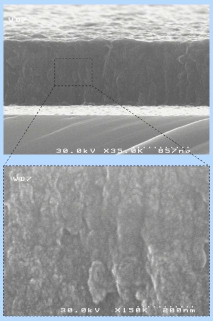
Abstract

Lead zirconate titanate (Pb(Zr,Ti)O3, PZT) is a favoured piezoelectric material for MEMS actuators because of its high piezoelectric coefficients and large coupling factors. To date, in MEMS applications, PZT has been configured as a unimorph with silicon providing the passive structural layers for a range of devices, including accelerometers, linked-cantilever filters, and FBARS. The same range of applications should be possible with diamond, namely NCD. NCD offers many attractive properties as a structural material with highly linear elastic properties up to high temperatures, high thermal conductivity and perhaps most important for high speed / high duty MEMS applications high stiffness at low density.

To obtain the perovskite structure of PZT with high piezoelectric activity, thin films must be deposited or annealed at high temperatures, somewhere in the range, 530 ℃ to 650 ℃, de pending on the PZT composition. To deposit PZT on top of NCD, consideration must be given to avoiding etching of the diamond in oxygen atmosphere at these high temperatures. A crucial issue has therefore been the development of good adhesion layers between the PZT and diamond film. In this paper we will report the deposition of sol gel derived PZT onto NCD and subsequent annealing. The diamond films had been grown on silicon by MPCVD. An SEM cross-sectional analysis of the diamond/PZT interface reveal a dense polycrystalline microstructure.

In addition, fabrication processes for incorporating these films into NCD-MEMS devices are demonstrated.

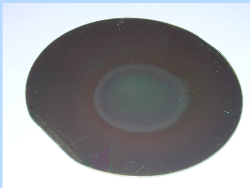
3D nanocrystalline diamond (NCD)



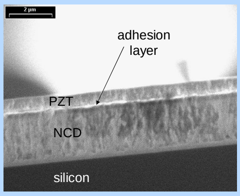
Material properties

	diamond	3D NCD (intr.)	Si (intr.)	PZT
Hardness [GPa]	100	100	13	19.4
Young's modulus [GPa]	1143	800	160	80
density [kg/m^3]	3520	3520	2330	7500
breakdown field [10^8 V/m]	10	10	0.5	10
electrical resistivity [Ωcm]	10^{12}-10^{16}	10^8	10^4	>10^{14}

PZT on 3D NCD

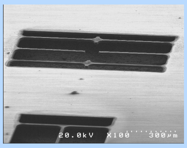


Sol-gel derived PZT on 2 inch NCD-on-silicon wafer

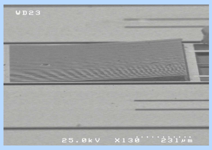


Cross-section view of PZT on NCD

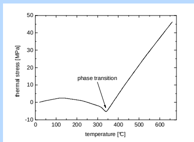
Thermal mismatch and stress



cantilever beams NCD
radius of curvature → ∞
t_{NCD}: 0.5 µm



cantilever array PZT on NCD
radius of curvature ~ 19 mm
t_{NCD}: 2 µm; t_{PZT}: 0.5 µm



calculated thermal mismatch of PZT to substrate after deposition

→ thermal stress in PZT less than 50 MPa up to 650 ℃
→ thermal stress of NCD controllable with deposition parameters (undoped from -200 MPa to +500MPa)
→ no stress gradient in films because of random oriented nanocrystalline structure

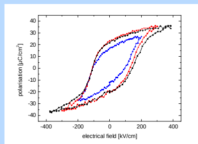
→ thermal mismatch of films at RT or temperature of operation can be widely compensated or controlled
→ deflection can be nearly fully compensated or controlled

PZT by sol-gel

Production of Sol-Gel:

- dissolving of $Pb(OAc)_2 \cdot 3H_2O$ in methanol
- dissolving of $Zr(OnPr)_4 \cdot {}^nPrOH$ and $Ti(O^nBu)_4$ in a mixed solution of acetic acid and methanol
- Mixing of solutions Pb and reflux
- adjustment of pH and PZT concentration with acetic acid
- filtering through 0.2 µm filter and adding of ethylene glycol

Hysteresis curve of PZT



Properties of sol-gel PZT

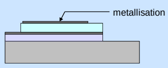
d_{31} [pm/V]	d_{33} [pm/V]	ε_{rel}	k_{31} [%]	k_{33} [%]
80	160	900	25	50

Fabrication technology of cantilever structure

deposition of NCD, adhesion and seeding metallisation, and PZT

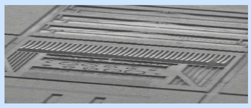
wet etching of PZT

dry etching of metallisation and NCD



deposition of top metallisation

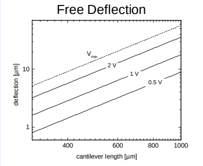
dry etching of silicon frame



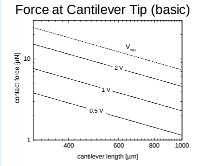
fabricated cantilever array

Switch application: Contact force on base plate (calculated)

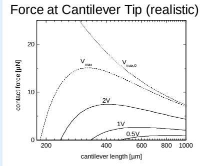
Free Deflection



Force at Cantilever Tip (basic)



Force at Cantilever Tip (realistic)



$$\delta_0 = \frac{3L^2}{2t} \cdot \frac{2AB(1+B)^2}{A^2B^4 + 2A(2B+3B^2+2B^3)+1} \cdot d_{31} \frac{V}{t_{PZT}}$$

$$F = \frac{3wt^2E_{PZT}}{8L} \cdot \frac{2AB}{(AB+1)(1+B)} \cdot d_{31} \frac{V}{t_{PZT}}$$

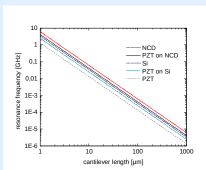
$$F = \frac{3wt^2E_{PZT}}{8L} \cdot \frac{2AB}{(AB+1)(1+B)} \cdot \frac{d_{31}}{t_{PZT}} \cdot \left(V - \frac{(AB+1)(1+B)}{2AB} \cdot \frac{2tg}{3L^2} \cdot \frac{t_{PZT}}{d_{31}} \right)$$

δ: deflection
L: length
t: overall thickness (2.1 µm)
t_{PZT}: thickness of PZT (1.6 µm)
$t_{diamond}$: thickness of diamond (0.5 µm)
E_{PZT}: Young's modulus of PZT (80 GPa)
$E_{diamond}$: Young's modulus of diamond (800 GPa)
$A = E_{diamond} / E_{PZT}$
$B = t_{diamond} / t_{PZT}$
d_{31}: transversal piezocoefficient (80 pm/V)
V: applied voltage
V_{max}: maximum applicable voltage (3.2 V)
w: cantilever width (300 µm)
F: force at cantilever tip

→ real structure possesses airgap in open state
→ effective contact force only in closed position
→ calculation for airgap (g) = 2 µm

based on the ref.: J. Zeng, L. Wang, J. Gao, Z. Song, X. Zhu, C. Lin, L. Hou, E. Liu, J. Crystal Growth 197 (1999) 874

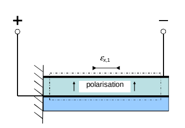
Resonance frequency (calculated)



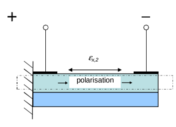
resonance frequency of different cantilevers with same geometry

→ high stiffness of NCD, low stiffness of PZT
→ low resonance frequency of PZT cantilevers
→ resonance frequency for PZT on NCD in MHz range for cantilevers < 60 µm
→ for identical geometry resonance frequency approximately doubled as compared to PZT on Si

Operating modes



transversal mode (d_{31})



longitudinal mode (d_{33})

Conclusion

- material system theoretically analysed in terms of thermal stress (concerning deposition temperatures), cantilever resonance frequency, cantilever deflection and cantilever tip force
- PZT on NCD deposited by sol-gel process
- test structures for determination of thermal mismatch of PZT and NCD fabricated
- fabrication technology for manufacture of cantilever actuators developed

→ Toolbox for development of unimorph cantilever switches and mechanical resonators developed