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Q-factor dependence of one-port encapsulated polysilicon resonator on reactive sealing pressure

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Abstract. *Micromachined encapsulated polysilicon resonators have been fabricated in different reactive sealing pressure, 200, 50 and 20 mTorr, in order to investigate the dependence of the Q-factors on the sealing pressure. Q-factors as high as 2700 have been measured. The experimental results show that the Q-factors of one-port encapsulated resonators are proportional to $1/p$ and the resonant frequency is independent of the sealing pressure. However, the measured Q-factors are more than two orders of magnitude lower than theoretical prediction.*

1. Introduction

Vacuum encapsulated micromachined resonators are very attractive for the precise measurement of quantities such as pressure, force and weight [1–8]. They offer high mechanical quality factors, high sensitivity and resolution, together with a semi-digital output. In 1988 Ikeda *et al* first fabricated single-crystalline silicon resonators housed in on-chip vacuum shells, using a self-aligned selective epitaxial technology in combination with selective anisotropic etching and hydrogen evacuation techniques [1]. Another micro resonator has been presented by Guckel *et al* in 1990 [3, 4]. They employed the polysilicon/silicon dioxide sacrificial layer etching technique to realize a similar structure. The most recent work in this area has been done by Tilmans *et al* in 1993 [5, 7, 8]. They used the same fabrication process that Guckel *et al* developed but realized an electrostatically driven vacuum encapsulated doubly supported polysilicon resonator.

Reactive vacuum sealing of the sacrificial layer etching channels by LPCVD Si_3N_4 is one of the most critical processes in fabricating encapsulated resonators, because the final cavity pressure and thus the Q-factors of the resonators are strongly dependent on the sealing process pressure. In the molecular regime, the mechanical quality factor Q_n of micromachined resonators as a function of the ambient pressure p can be expressed as [5, 9]:

$$Q_n = \frac{3}{8\sqrt{6}}\frac{\alpha_n^2}{p}\left(\frac{h}{l}\right)\left(\frac{\pi E\rho RT}{M}\right)^{1/2} \qquad (1)$$

where α_n is a constant depending on the boundary conditions and on the mode of vibration n, h and l are the thickness and the length of the resonator, E and ρ are Young's modulus and the density of the resonator beam, respectively, R is the universal gas constant, T is the absolute temperature and M is the molecular mass of the gas in the cavity.

In this study, we experimentally investigated the quality factor dependence of the one-port electrostatically driven encapsulated polysilicon resonator on the reactive sealing pressure. The resonators have been sealed in three different process pressures, 200, 50 and 20 mTorr. The experimental results are given.

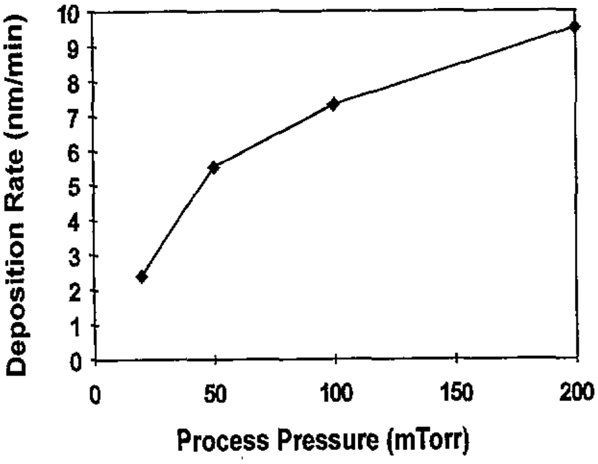

Figure 1. LPCVD Si_3N_4 deposition rate as a function of process pressure ($T = 850\,°C$).

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Table 1. Parameters of LPCVD Si_3N_4 reactive sealing process[a].

Wafer No	$P_{process}$ (mTorr)	$T_{process}$ (°C)	NH_3 (sccm)	DCS (sccm)	Time (min)	Deposition (nm min^{-1})	Thickness (nm)	P_{cavity} (mTorr)
13	20	850	20	6.7	82	2.4	194	5.88
14	50	850	66	22	36	5.5	205	14.70
15	200	800	66	22	36	5.5	197	61.53

[a] DCS = dichlorosilane, $SiCl_2H_2$; sccm = standard cubic centimetres per minute.

2. Experimental details

The LPCVD Si_3N_4 deposition rates in different process pressures have been determined experimentally (see figure 1). The overall chemical reaction for LPCVD Si_3N_4 reactive sealing process is [7]:

$$3SiCi_2H_2 + 10NH_3 \rightarrow Si_3N_2 \downarrow + 6H^2 \uparrow + 6NH_4Cl \uparrow \quad (2)$$

The final cavity pressure after sealing is a function of the processing pressure, temperature, the gas flows, the reaction products, subsequent diffusions and the change of the cavity volume before and after sealing [4]:

$$P_{cavity} = P_{process} \frac{V_{unsealed}}{V_{sealed}} \frac{T_0}{T_{process}} \frac{n_{right}}{n_{left}} \quad (3)$$

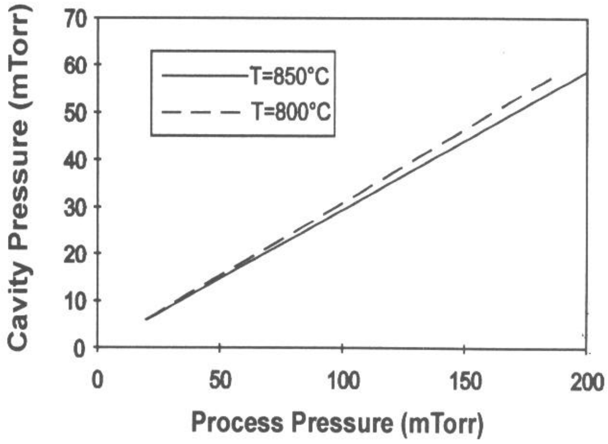

Figure 2. Dependence of final cavity pressure on sealing process pressure.

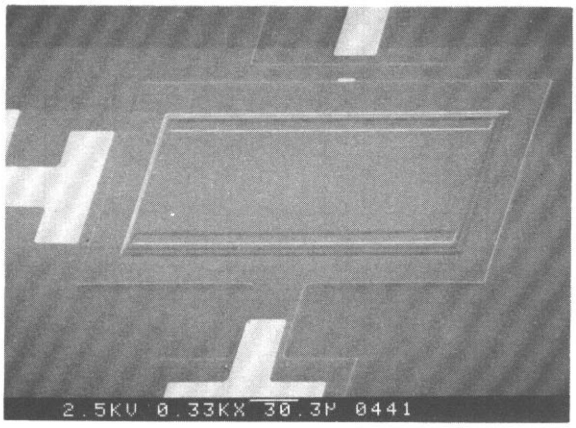

Figure 3. SEM photo of an encapsulated resonator.

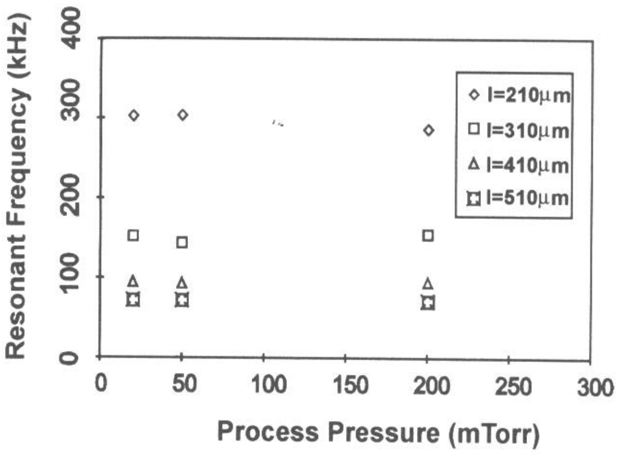

Figure 4. The first-order resonant frequency is independent of the reactive sealing pressure.

where T_0 and $T_{process}$ denote the room temperature and the process temperature respectively, $V_{unsealed}$ and V_{sealed} represent the cavity volume before and after sealing, $P_{process}$ is the process pressure, and n_{right}/n_{left} denotes the mole ratio of gaseous products and reactants.

The change of the volume of the cavity is mainly due to the deflection of the cap after sealing:

$$\frac{V_{unsealed}}{V_{sealed}} = \frac{l_c b_c (h_{c1} + h_{c2})}{l_c b_c (h_{c1} + h_{c2} - \delta h)} = \frac{h_{c1} + h_{c2}}{h_{c1} + h_{c2} - \delta h} \quad (4)$$

where l_c and b_c denote the length and width of the cavity, respectively, h_{c1} and h_{c2} denote the thickness and the first and the second sacrificial layer respectively, and δh denotes the deflection of the cap after sealing. In our case an average deflection of 500 nm of the cap after sealing has been measured. For $h_{c1} = h_{c2} = 1.5$ μm, we obtain $V_{unsealed}/V_{sealed} \simeq 1.2$.

In equation (2), n_{right}/n_{left} equals 12/13. The dependence of final cavity pressure on the sealing process pressure at different process temperatures is shown in figure 2. The parameters of reactive sealing process are shown in table 1.

3. Results and discussion

A SEM photo of the encapsulated polysilicon resonator is shown in figure 3. The quality factors are extracted from the admittance plots, which are measured by using a HP4149A impedance analyser.

For resonators sealed in 20 mTorr, Q-factors as high as 2700 have been measured. The measured mechanical

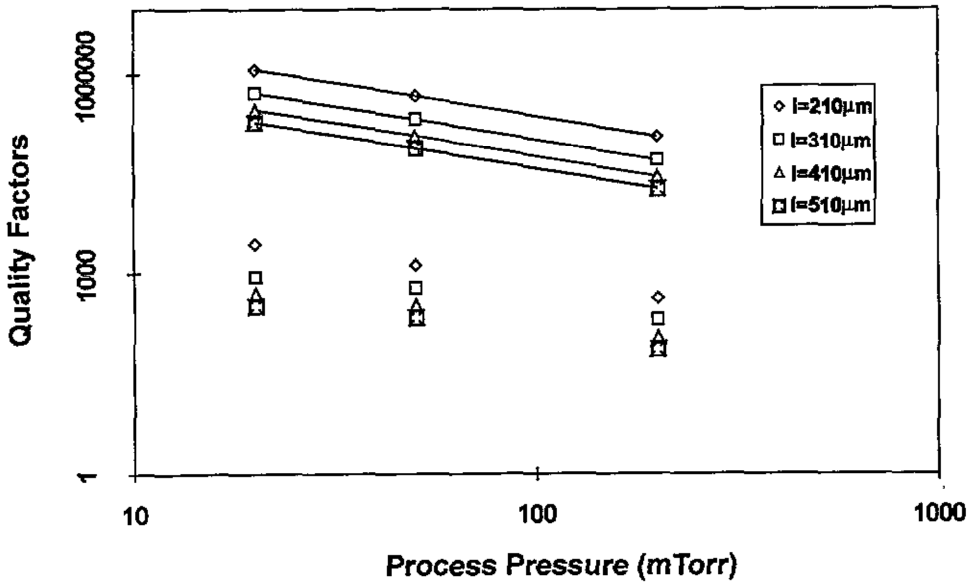

Figure 5. Q-factor dependence of one-port encapsulated resonators on the sealing pressure for all four beam lengths. The width and thickness of all four beams are 100 μm and 1.5 μm. Symbols linked by lines are theoretical prediction, and those without lines are measured results.

quality factors for all four kinds of resonators are, as expected, proportional to $1/p$. The measured first-order resonant frequency of all four kinds of resonators are independent of the sealing pressure (figure 4). These results show that the resonant beams are working in the molecular regime and that momentum damping is the dominant damping mechanism [5, 9]. However the value of Q-factors are more than two orders of magnitude lower than theoretical prediction (figure 5). The reason for this discrepancy is under investigation. But we believe that it is most likely due to the fact that the assumption of free space surrounding the resonator is not true. In deriving the relationship between quality factors and surrounding pressures of micromachined beams, it was assumed that the surfaces except the one end support are very far away from the vibrating beam and will not influence the damping [9]. However, in encapsulated resonators, the beams are located in two narrow gaps. The ratio of the thickness of the gap and the width of the beam is 1/100. In this case, the influence of the surfaces of the cap and the substrates on the damping should be taken into account.

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