Electromechanical devices utilizing thin Si diaphragms

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Heavy boron diffusion followed by selective etching has been used to produce uniform edge-supported Si diaphragms with thickness in the 1–3-μ range and areas up to 5 cm^2. These diaphragms have numerous applications in the fabrication of rugged reliable electromechanical devices which are compatible with IC technology. In this paper we describe the performance of an electrically tunable resonant cavity which operates in the 10–12-kHz range with Q as high as 23000. Devices based on this cavity structure include pressure transducers, microphones, speakers, tunable filters, and oscillators.

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Despite the fact that diffusion has been used for many years to provide controlled doping of Si, very little is known about the detailed mechanisms, microstructure, and intermediate surface phases which are relevant at extremely high doping levels. We have recently been engaged in a study of the surface phases which result when very high concentrations of boron are diffused into Si in an oxidizing ambient.[1,2] Careful Auger analysis of the sample after such diffusions indicates that the material exhibits four distinct regions as illustrated in Fig. 1(a). The outermost layer consists of ~100 Å of B_2O_3. This is followed by several hundred Å ($\lesssim$1300 Å) of mixed B_2O_3 and SiO_2. The third layer is a Si-B surface phase. The thickness and composition profile of this phase depend on processing conditions and will be discussed in a forthcoming publication. Here, it is sufficient to note that there is always a very high ($\sim 10^{23}$ cm^{-3}) B concentration near the interface between layers 2 and 3, followed by a plateau region in which the B concentration is above the solubility limit ($>2\times10^{20}$ cm^{-3}). Near the back of layer 3, the B concentration drops fairly abruptly to levels at which the B can be accommodated substitutionally in the Si lattice (low 10^{20} cm^{-3}). This defines the onset of region 4 which consists of normal B-doped Si.

Experiments with hydrazine and KOH indicate that the Si-B surface phase (layer 3) is insoluble in hydrazine and only slightly soluble in KOH.[2–4] This, and the fact that these etches are selective in the sense that they yield etch rates in Si that are largest along ⟨100⟩ directions,[5] allow the fabrication of very thin edge-supported films with thicknesses from 1–3 μ and areas up to 5 cm^2. These films can consist of layers 1–3, or of layer 3 alone, depending on whether or not the thin glass layers are stripped off. In either case, the films are mechanically strong and can withstand further processing such as drive-ins or additional diffusions. They are also highly conductive, with sheet resistances typically in the 1–10-$\Omega/\square$ range.

Given the technology for producing thin mechanically strong diaphragms in Si, a variety[6] of interesting new device structures becomes feasible. In the present paper one such structure, the sealed cavity illustrated in Fig. 1(c), will be discussed. This geometry immediately suggests applications which utilize either the static (pressure sensitive) or dynamic (electromechanically resonant) response of the cavity.

In order to test the feasibility of using Si diaphragm cavities as pressure sensors, a $0.8\times0.8\times2\times10^{-4}$-cm diaphragm was mounted on a pressure reference and center deflections were measured (with a microscope) as a function of pressure. The response in the low-pressure range was linear with a slope of 50 dyn/cm^2 per micron of center deflection. The specific pressure sensitivity is, of course, dependent on the lateral dimensions and thickness of the diaphragm. Other diaphragms of a comparable area have exhibited pressure sensitivities ranging from 35 to 200 dyn/cm^2 per micron of deflection. Since deflections of a few angstroms are easily detected capacitively, the possibility exists for fabricating extremely sensitive pressure transducers.

In order to check the ac response of Si diaphragm cavities, a recess was etched in a piece of optical quality Pyrex and metallized to form an air gap (~8 μ) and one of the capacitor plates. A Si diaphragm ($0.8\times0.8\times2.4\times10^{-4}$ cm) was then mechanically clamped over the recess (electrostatic bonding has also been used successfully to join the Si and Pyrex); and the entire structure was placed in a vacuum system for measurement. This test structure exhibited a very sharp ($Q\approx 23000$) resonance at 12.5 kHz. Furthermore, it is clear that if a dc bias is applied to the cavity, the electric field can easily generate electrostatic forces of the order to 50 dyn/cm^2, resulting in a static deflection of the diaphragm and a change in the resonant frequency. This has been confirmed experimentally and the data are shown in Fig. 2. Under static deflection, the cavity exhibits two resonances: a series resonance which was

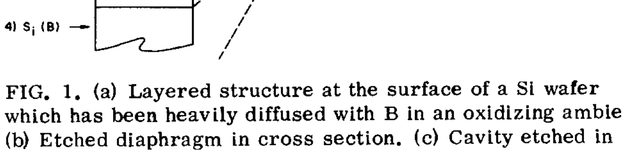

FIG. 1. (a) Layered structure at the surface of a Si wafer which has been heavily diffused with B in an oxidizing ambient. (b) Etched diaphragm in cross section. (c) Cavity etched in Pyrex and sealed with a Si diaphragm.

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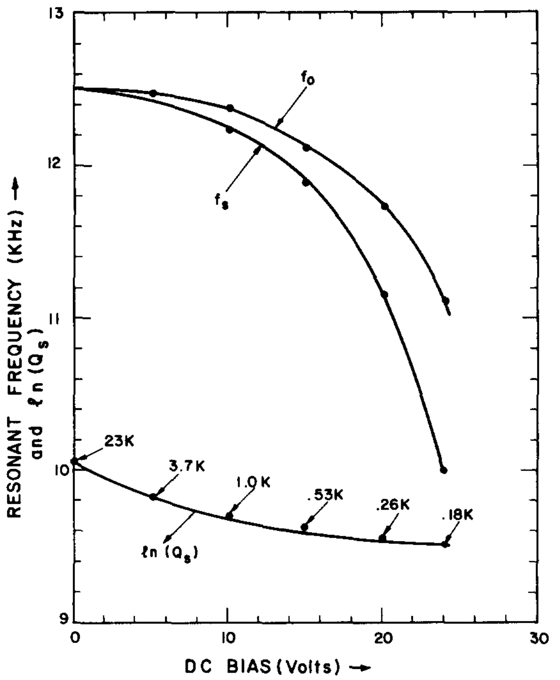

FIG. 2. The series (f_s) and parallel (f_0) resonant frequencies and cavity Q for a cavity fabricated as shown in Fig. 1, as functions of applied dc bias. Cavity dimensions: 0.8×0.8-cm area 2.4×10^{-4}-cm diaphragm thickness, 8×10^{-4}-cm cavity thickness.

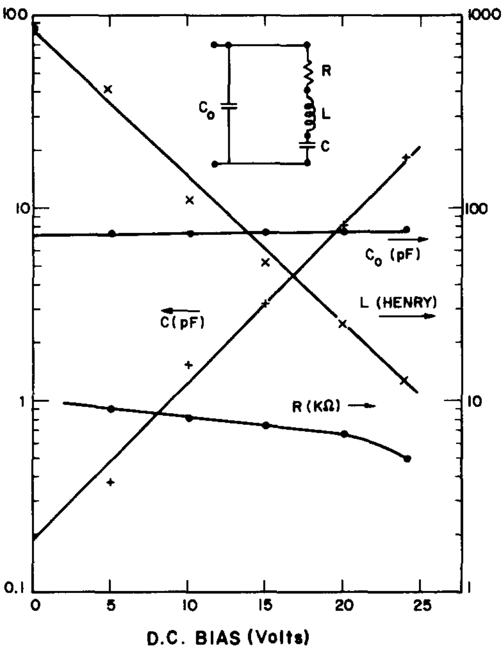

FIG. 3. Equivalent circuit parameters for the cavity of Fig. 2 as functions of applied dc bias.

measured by driving the cavity with a voltage source, and a parallel resonance which requires current source excitation. The quality, or Q, of the resonance was measured independently by pulsing the cavity and observing the ranging in the terminal current or voltage between pulses. Of particular note in Fig. 2 are (1) the broad tuning range demonstrated and (2) the extraordinarily high Q of the resonance. The Q data shown in Fig. 2 were obtained at a background gas pressure of 10^{-6} mm Hg. Studies of the dependence of Q on gas pressure and gas species are underway. Typical Q's at atmospheric pressure are ~200. It will undoubtedly prove possible to raise the Q further by metalizing the diaphragm to reduce surface-current losses.

By analyzing the pulsed and steady-state ac response of the cavity as a function of dc bias, it was possible to develop an equivalent circuit for the cavity. The equivalent circuit and values for the circuit elements as functions of dc bias are shown in Fig. 3.

From the dimensions of the diaphragms, it may appear that an adequate mechanical description could be based on the theory of membranes (negligible thickness, arbitrary slope along the line of support). It can be shown, however, that such models predict instabilities which are not experimentally observed, and that a correct model must be based on the theory of thin plates (finite thickness, zero slope along the line of support) including stresses within the plate.[2]

The results reported here demonstrate the availability of a technology for fabricating a new class of electromechanical devices and transducers, fully compatible with the Si IC technology. Tunable filters, optical interference filters, and more complex multicavity structures have already been demonstrated. Work is continuing on these devices and on developing a better understanding of the composition and microstructure of the films.

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