Physica B 165&166 (1990) 125–126
North-Holland

ANOMALOUS LOW TEMPERATURE MECHANICAL PROPERTIES OF SINGLE-CRYSTAL SILICON

R.E. MIHAILOVICH, J.M. PARPIA

Laboratory of Atomic and Solid State Physics, Cornell University, Ithaca, New York 14853-2501, USA

We have measured the low temperature mechanical properties of a high Q oscillator fabricated from single crystal silicon. Operated at strains of 10^{-7}, the oscillator exhibits unusual behavior in both the dissipation and resonant frequency. In addition, we have performed systematic frequency sweeps through resonance at varying strain amplitudes. We observe the dramatic onset of non-linear behavior at temperatures below a few hundred millikelvin.

1. INTRODUCTION

Anomalies in the low temperature mechanical properties of metal oscillators have been observed in many experiments. These oscillators were typically machined from alloys of BeCu or AgCu and then heat treated to enhance the Q. Similar anomalous results were obtained with a silicon oscillator by Kleiman et al.(1) We have undertaken a further study of these unusual mechanical properties in order to better understand the behavior of these devices. Silicon is ideal for such studies, as it is available in high-purity-single-crystal wafers which do not require treatment to increase the Q. The absence of conduction electrons also simplifies the system. Appropriate design allows us to operate at high frequencies, an advantage in high Q oscillators as it shortens the response time.

2. APPARATUS

The oscillator is fabricated from a double-side polished, 350μm thick < 100 > wafer, doped to a resistivity of 4-8 ohm-cm. We used photolithographic patterning and anisotropic etching techniques to fabricate the oscillator, which is of a double-paddle design (see Figure 1) with two inertial elements (the head and paddles) and two torsional elements (the neck and tail).

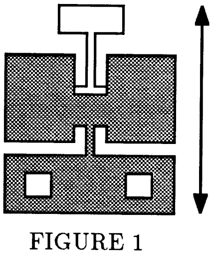

FIGURE 1
Double paddle silicon oscillator with evaporated gold (shaded region) covering paddles, tail and holed base.

Anisotropic etching of the < 100 > wafer produces bevelled edges, which when properly aligned during etching, produces neat corners at the junction of torsion rods and inertial elements. A gold film is evaporated on the paddles, tail and base of the oscillator, to provide a ground plane for capacitive drive and detection as well as a thermal conduction path. The oscillator is clamped to a copper base with screws after the base is coated with a thin layer of vacuum grease.

3. RESULTS

The double paddle oscillator has several resonances. The experiments reported here were obtained by operating in the antisymmetric torsional mode, where the strain is confined to the upper torsion rod, thus minimizing potential clamping losses. At low temperatures, the typical Q is $> 2 \times 10^6$. We plot the dissipation and resonant frequency of the oscillator measured at a constant strain amplitude of 10^{-7} in Figure 2.

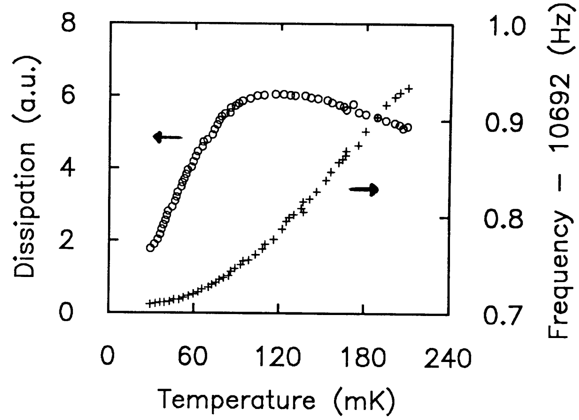

FIGURE 2
Dissipation (o) and resonant frequency shift (+) at a constant strain amplitude of 10^{-7}.

Both the measured quantities exhibit the anomalous behavior in the temperature range below 200 mK. The dissipation shows a gentle peak, and then decreases linearly with temperature below 100 mK. The shift of the resonant frequency is also proportional to the temperature. Both of these results are qualitatively similar to those reported by Kleiman et al.(1)

To better characterize this anomalous behavior, we used a frequency synthesizer to continuously sweep through the resonance. These sweeps were done at constant drive levels, producing peak strains as large as 2×10^{-6}. Figure 3 shows results obtained for scans conducted at 800 mK. The response is characteristic of a nearly linear oscillator, with a symmetric amplitude and little reduction in the Q with higher strain.

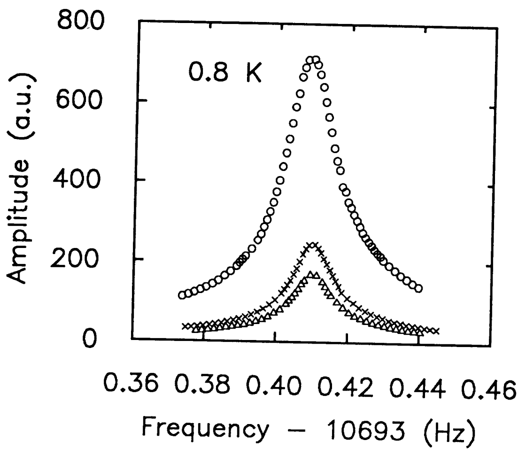

FIGURE 3
Frequency sweeps at T=0.8K for drives of 780 mV (o) 210 mV (×) and 156 mV (△).

Figure 4 shows the results of scans taken at a temperature of 15 mK at different drive levels. The response is typical of an oscillator with pronounced nonlinear characteristics, showing a skew to higher frequencies with increasing amplitude. At the largest drive level, the response is clearly hysteretic. An examination of the hysteretic trace serves to rule out self-heating. At the lowest excitation shown, the oscillator response continues to be asymmetric, suggesting that the strain amplitude for linear response is less than 10^{-8} at this temperature. Measurements at 200 mK, not presented in this work, show a much less pronounced skewness and only at the highest drive levels. A frequency shift of the same magnitude as shown in Figure 4 was observed by Kleiman et al., but with a decrease in frequency as the drive was increased.

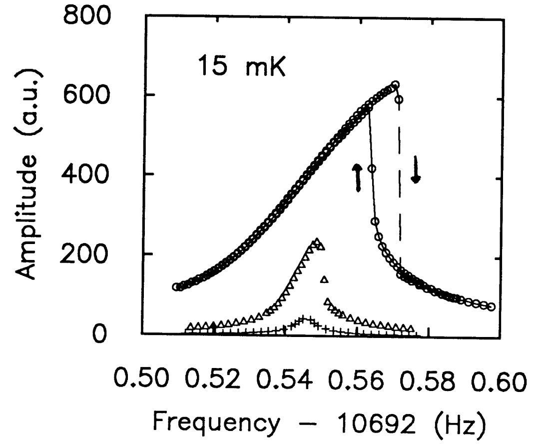

FIGURE 4
Frequency sweeps at T=15 mK for drives of 780 mV (o) 110 mV (△) and 20 mV (+). At the 780 mV drive level, the hysteretic response is shown as the dashed line (sweeping up in frequency) and as the solid line (sweeping downward).

4. CONCLUSION

It is our contention that the anomalous mechanical behavior is accompanied by a remarkable nonlinear response of the oscillator. We base this on the absence of the skewed behavior at high temperatures where the response is "normal" and the onset of the nonlinear response in the regime where the frequency and dissipation behave anomalously. We are continuing the investigation to gather more data for comparison to theoretical models and to previous experimental work.

ACKNOWLEDGEMENTS

This research is supported through a grant from the NSF through the Cornell Materials Science Center DMR-8818558 and the NSF through DMR-8820170. We would like to acknowledge the support and collaboration of L. Pollack, E. Smith and R.C. Richardson.

REFERENCES

(1) R. N. Kleiman et al., Phys. Rev. Lett., 59, 2079, (1987) and references therein.