Cantilever deflection measurement and actuation by an interdigitated transducer

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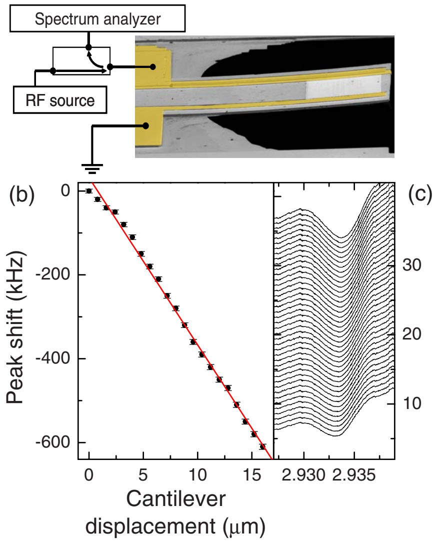
A scheme that allows all-electrical high-bandwidth readout of a cantilever deflection by means of an integrated interdigitated transducer is presented. The present approach takes advantage of the piezoelectricity of the chosen cantilever substrate material to generate and detect surface-acoustic-waves by means of an interdigitated transducer (IDT) and to determine cantilever deflections. We shall also show that the same IDT can be used to excite the oscillation modes of the lever. Our scheme is compatible with implementations exploiting wireless excitation and readout and in mass sensing applications. © *2010 American Institute of Physics*. [doi:10.1063/1.3407516]

Atomic force microscopy (AFM)[1] is a powerful tool for the characterization of surfaces at the nanoscale.[2] In its simplest implementation, surface properties are probed by scanning a sharp tip mounted at one end of a cantilever and measuring its deflection. Detection modes include static (contact) and dynamic modes.[3] In the latter case, tip-to-sample interactions can be monitored because they induce a detectable change in the lever mechanical resonance frequency and oscillation amplitude. Implementation of dynamic modes requires the lever to be excited close to one of its resonances, typically by means of an external dither piezo. This has some disadvantages, however, and it may excite oscillations of the entire chip supporting the lever or waves in the medium surrounding the lever (particularly in the case of operation in liquids) thus making the identification of cantilever resonances less reliable.[4] To circumvent this issue, direct excitation of the lever is sometimes preferred.[5–8] For what concern cantilever-motion detection, one of the most used approaches is based on optical detection, interferometric or via optical-lever amplification, of the deflection.[9] Other methods[10] do not require an external laser source: piezoresistive[11] and piezoelectric[12] levers, despite a lower sensitivity, offer the advantage of compactness and ease of use since they do not require the precise alignment of the optical setup. This makes them particularly appealing for cryogenic and ultrahigh-vacuum systems. In turn, electric readout of the deflection is the technique of choice for the implementation of detector arrays. Nevertheless, the need to individually access each cantilever, poses a severe limit to the scalability of these systems.

In this letter a scheme is presented that allows the direct excitation of cantilever oscillation modes and an all-electrical high-bandwidth readout of its deflection by means of a single interdigitated transducer (IDT) fabricated on the lever surface. As we shall discuss below, it can be extended to wireless schemes and to fast, sequential readout of cantilever arrays. This feature makes our scheme particularly suitable for the implementation of large arrays of mass sensors based on chemically functionalized cantilevers.[13] Our approach is based on the choice of a piezoelectric cantilever material, i.e., GaAs. This allows the generation and detection of surface-acoustic-waves (SAWs) by means of an IDT together with the excitation of lever oscillation modes by means of the same IDT.

Our cantilevers are fabricated by selective wet etching on a heterostructure composed of a 2 μm thick GaAs top layer and five periods of AlAs/$Al_{0.3}Ga_{0.7}As$ (50/50 nm) acting as etch stop layer grown on a GaAs wafer. A nonselective chemical etching ($H_2SO_4:H_2O_2:H_2O=1:8:1$), followed by a selective etching (citric acid: $H_2O=3:1$), were used to remove the GaAs substrate. The cantilever geometry was defined by chemical etching of the remaining epitaxial layers. Levers were fabricated with lengths from 140 to 245 μm and a width $W=120$ μm.

An IDT, composed of 100 pairs of Al fingers with a periodicity of 1 μm, was evaporated on the top surface of



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each cantilever. The resonance frequency f_{IDT} was determined by measuring the power reflected by the IDT as a function of the excitation frequency with the setup shown schematically in Fig. 1(a). At rest position, reflected power data show $f_{\mathrm{IDT}}=2.934$ GHz [see Fig. 1(c)], a value that matches the expected frequency (approximately 3 GHz, for 1 μm wavelength SAWs on GaAs).

Bending the cantilever induces a shift in f_{IDT}, which is given by the ratio between the surface sound velocity (v_s) and the IDT fingers periodicity (d), by changing d of an amount $\delta d/d \approx ht/L^2$, where h is the displacement of the cantilever free edge from its rest plane, t is the cantilever thickness, and $L=245$ μm its length (this is a first-order approximation and, e. g., changes in v_s induced by strain are neglected). Under the assumption that the SAW penetration into the cantilever is negligible, i.e., $d \ll t$, the fractional change in the resonance frequency is $\delta f_{\mathrm{IDT}}/f_{\mathrm{IDT}}=-\delta d/d$. In the present case since $t=2$ μm, the frequency shift is expected to be $\delta f_{\mathrm{IDT}}/f_{\mathrm{IDT}} \lesssim -\delta d/d=-ht/L^2$, yielding a frequency shift per unit deflection $\lesssim 100$ kHz/μm.

A static deflection of the cantilever was induced by pushing its free edge with a rigid tip controlled by a calibrated piezotranslator. The power reflected as a function of the IDT excitation frequency at different deflection values is shown in Fig. 1(c) and confirms a linear shift of f_{IDT} in a broad deflection range [see Fig. 1(b)]. The experimental slope (k) of f_{IDT} versus h was $k \approx 41.5$ kHz/μm, within the expected range of the theoretical value.

In order to test the dynamic response of our readout scheme, cantilevers were mounted on a holder equipped with a dither piezo capable of exciting cantilever oscillations up to 1 MHz. Cantilever oscillations induce a periodic shift of f_{IDT} of the form: $f_{\mathrm{IDT}}(t)=f_{\mathrm{IDT}}^{(\mathrm{rest})}+kA\cos(2\pi f_{\mathrm{piezo}}t)$, where f_{piezo} is the dither-piezo-excitation frequency, $f_{\mathrm{IDT}}^{(\mathrm{rest})}$ is the IDT resonance frequency at rest position, and A is the amplitude of cantilever oscillations. In this configuration the RF signal reflected by the IDT is amplitude-modulated at f_{piezo}. For small oscillations, $A \ll \Gamma/k \approx 100$ μm, where Γ is the width of the resonance peak, the time-dependent voltage of the signal reflected by the IDT can be approximated by:

$$\begin{aligned} V(t) &\propto \sqrt{P[f-f_{\mathrm{IDT}}(t)]}\cos(2\pi f t) \\ &\simeq [1-S(t)]\sqrt{P_0}\cos(2\pi f t), \end{aligned}$$

where $P(f-f_{\mathrm{res}})$ is power reflected by an IDT with a resonance frequency of f_{res} when excited at a frequency f, $P_0 = P[f-f_{\mathrm{IDT}}^{(\mathrm{rest})}]$, and $S(t)=(1/2P_0)(\partial P_0/\partial f)kA\cos(2\pi f_{\mathrm{piezo}}t)$. $S(t)$ is the portion of signal modulated at f_{piezo}. It would appear in the spectrum of $V(t)$ as side bands of the peak at f, with an intensity proportional to A. To maximize the measurement sensitivity, f was set at $f_{\max}=2.924$ GHz, which is the value that maximizes the function $s(f) = (1/\sqrt{P_0})(\partial P_0/\partial f)$.

Figure 2(a) shows the power spectra of the signal reflected by the IDT for two different values of f_{piezo} at $f=2.924$ GHz. Both spectra show a main peak at f and two side bands at a distance f_{piezo} from the central peak, corresponding to the amplitude modulation of the reflected signal. In tapping-mode or noncontact implementations of the present scheme, the amplitude of the side bands should be used as the feedback signal for the AFM controller. Figures 2(b) and 2(c) plot the spectra of the reflected rf signal as a function of f_{piezo}. Side bands are clearly visible at $f_{\mathrm{piezo}}^{(1)}=108.5$ kHz, $f_{\mathrm{piezo}}^{(2)}=300$ kHz, $f_{\mathrm{piezo}}^{(3)}=560$ kHz, and $f_{\mathrm{piezo}}^{(4)}=577$ kHz. A comparison with the frequencies of the oscillation modes of the cantilever, determined with a conventional optical-lever setup [Fig. 2(d)], confirms that the values of $f_{\mathrm{piezo}}^{(1)}$ and $f_{\mathrm{piezo}}^{(2)}$ correspond to the first two oscillation modes of the lever. $f_{\mathrm{piezo}}^{(3)}$ and $f_{\mathrm{piezo}}^{(4)}$ lie outside of the bandwidth of the photodiodes used in the optical-lever setup and correspond to the third mode, probably split due to the cantilever connection to the chip. We note that the intrinsic response time of the system is limited only by the SAW transit time in the IDT region. This yields a high-frequency cutoff in excess of 20 MHz for the chosen geometry, allowing very-high-bandwidth dynamic measurements.

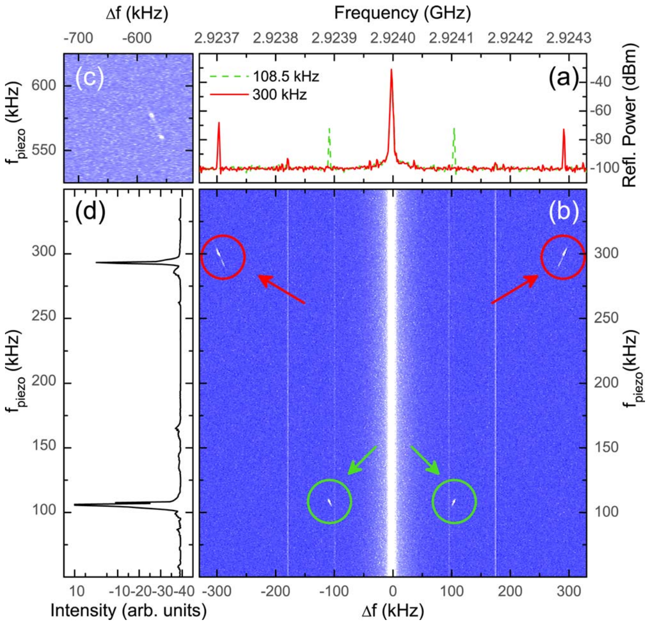

FIG. 2. (Color online) (a) Spectrum of the signal reflected by the IDT for two mechanical excitation frequency values (f_{piezo}) corresponding to the first two cantilever resonances. The IDT excitation frequency was set to $f=2.924$ GHz; (b), (c) spectrum of the reflected signal as a function of the frequency shift Δf with respect to f and of the piezoexcitation frequency (f_{piezo}). Four resonances, marked by arrows, can be observed. The vertical features at ±100 kHz and ±180 kHz are artifacts of the measurement system; (d) cantilever mechanical oscillation modes determined by a conventional optical-lever setup.

Speed of sound is temperature dependent and it is important to estimate how temperature drift can impact the present scheme. To this end we note that in our implementation the maximum of $s(f)$ at $f_{\max}$ has a full width at half maximum $\sim$3 MHz (data not shown), corresponding to $\sim$28 °C (the temperature coefficient of sound velocity in GaAs is $\alpha=35$ ppm/°C (Ref. 14) for SAW propagation in GaAs along the ⟨110⟩ direction). Temperature control well within this range can be easily achieved in any realistic implementation.

The piezoelectricity of the cantilever substrate material makes it possible also to excite lever oscillations by means of the same IDT used for motion detection. Figure 3(a) shows the oscillation amplitude in one of the cantilevers studied as a function of the frequency of the IDT excitation signal. The sharp peak observed at 27 kHz corresponds to the fundamental flexural mode of the cantilever and demonstrates that it is possible to excite mechanical oscillations by

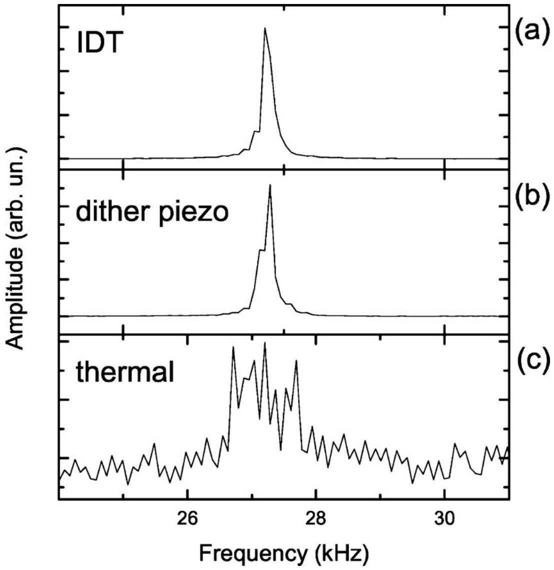

FIG. 3. [(a) and (b)] Oscillation amplitude of the cantilever as a function of the excitation frequency applied to the IDT (a), and to the dither piezo (b). (c) Spectrum of the cantilever deflection without external excitation showing the thermal motion. Data were taken with a conventional optical-lever setup.

means of IDTs. Identification of the peak was carried out by measuring the oscillation amplitude as a function of the dither-piezo-excitation frequency [Fig. 3(b)] and without excitation to detect thermal motion [Fig. 3(c)].

We believe these results can find broad applications for the realization of ultrafast AFM schemes. In particular, we would like to remark that there are very well known schemes to allow measuring wirelessly[15] the resonance frequency of an IDT, opening the way to the implementation of wireless rf cantilevers. Based on this, arrays of chemically functionalized cantilevers that are already employed in gas-sensing systems could be excited and read sequentially by tuning the IDT of each cantilever to a specific frequency. In conclusion, we have presented an all-electrical scheme to excite a cantilever and detect its motion based on an IDT. Cantilever deflection induces a detectable shift in the resonance frequency of the IDT. Owing to the piezoelectricity of the substrate material, the same IDT can be used to excite the mechanical oscillation modes of the lever.

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