Nonlinear SAW Propagation in Thin-Film Systems with Residual Stress

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Introduction

- Thin-film deposition processes can create large residual stresses which change the film’s mechanical properties and therefore its performance in a product.
- Residual stress affects the SAW velocity dispersion through the acoustoelectric effect, but the changes are often very small.
- Finite-amplitude SAWs, which nonlinearly generate harmonics as they propagate, may be more sensitive to stress because the combined effects of nonlinearity and dispersion are cumulative with distance.
- Numerical results are presented which compare velocity dispersion, waveform distortion, and harmonic generation for monofrequency SAWs propagating in systems with unstressed and compressively stressed Ge films on a Si substrate.

Dispersions and Nonlinearity

Consider the following snapshots of evolving waveforms in the retarded frame (moving at V0).

- Surface acoustic waves are a type of vibrational wave which occur near the surface of a solid half-space.
- Almost all the energy of a SAW is localized within a wavelength λ of the surface, potentially resulting in large surface strain amplitudes and nonlinear effects.
- Questions: How do SAWs propagate in stressed thin films? How big are the linear and nonlinear effects? Can SAWs evaluate stress in thin films?

Surface Acoustic Waves

- Without a film, SAWs are nondispersiv relative to one another causing complicated waveforms and harmonics.
- Without a film, SAWs are nondispersive, i.e., all frequency components travel at the same velocity.
- With a film of thickness δ, the lower frequency components (δ < δ) travel near the SAW velocity of the substrate, while the higher frequency components (λ < λ) travel near the SAW velocity of the film.
- Result of film on SAW: Various frequencies of the waveform disperse relative to one another.
- How do SAWs propagate in stressed thin films? How big are the linear and nonlinear effects? Can SAWs evaluate stress in thin films?

SAW Frequency Dispersion

- Wave equation for the thin film system:

\[
\frac{\partial^2 u}{\partial t^2} - \frac{1}{c^2} \frac{\partial^2 u}{\partial x^2} = \frac{\partial^2 u}{\partial y^2}
\]

- Waveforms exhibit significant distortion and harmonic generation with some dispersion.

- Assumptions include plane wave propagation and equibiaxial, homogeneous, static stress only in film.
- Equations are solved for the SAW velocity by a Green’s function technique to produce the dispersion relations.

Linear Theory

- Frequency domain evolution of a SAW velocity waveform is described by the coupled system:

\[
\frac{\partial^2 \phi}{\partial t^2} = \frac{1}{c^2} \frac{\partial^2 \phi}{\partial x^2} + \sum_{m=0}^{\infty} S_m \phi^{m+1}
\]

- Nonlinear Theory

- Thin films cause dispersion (phase shifts) between frequency components of SAWs. With finite-amplitude SAWs, nonlinearly generated harmonics disperse relative to one another causing complicated evolution of waveforms and harmonics.
- Linear SAWs: Stress causes small changes in wave velocity (1 to 3%).
- Nonlinear SAWs: Moderate dispersion Stress causes a shift in magnitudes and phases of the harmonics. Maximum effects occur at longer propagation distances and higher harmonics (20 to 60%).

Conclusions

- Nonlinear SAWs. Strong dispersion Strong dispersion results in only limited harmonic generation but with spatial oscillations in magnitude. Stress causes extrema of the harmonic curves to shift around 5% for every nonlinear length scale traversed.

Future Work

- Moderate Dispersion (D = 0.26)

- Harmonic magnitudes and phases between the stressed and un-stressed cases start to differ noticeably for X > 1.5.

- Without a film, SAWs are nondispersive, i.e., all frequency components travel at the same velocity.

- Strong Dispersion (D = 1.30)

- Harmonic magnitudes exhibit growth and decay cycles, while the phases show much dispersion.

- With a film of thickness δ, the lower frequency components (λ < λ) travel near the SAW velocity of the substrate, while the higher frequency components (δ < δ) travel near the SAW velocity of the film.

- Assumptions include plane wave propagation and equibiaxial, homogeneous, static stress only in film.

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