LASER-BASED INVESTIGATIONS OF SURFACE ACOUSTIC WAVES

A.G. Every
University of the Witwatersrand
Johannesburg, South Africa

Collaborators:
J. D. Comins, Wits University
A. A. Maznev, MIT
Gold Mining on the Witwater
Petrochemical Industry: SASOL Oil from Coal Complex
Power Generation and

Gariep Dam

Koeberg Nuclear Power Plant, Cape Town

Arnot Power Station
Infrastructure: Road Transport
Railways and Harbours
Air Transport

Oliver Tambo International Airport, Johannesburg

“If God had meant man to fly...”
Communications

South Africa to launch third satellite into space in November 2013

Mail runner: Early Colonial Period
Diversified Manufacturing Industry
SAINT Council

From left: Manfred Johannes, Immediate Past President, Simon Wilding, Vice President, Abby Chiswo,
Johan Gerber, Honorary Treasurer, Garth Appel, Lew Wells, Ben Beetge, President, Harold Jansen,
Robin Marshall, Keith Cain, Honorary Secretary. (absent Floyd Rezant and Hennie de Wet)
SAINT Supported Schools of NDT

The Southern African Institute of Welding (SAIW)

African NDT Centre

Vaal University of Technology

The School of Applied Non-Destructive Examination

The Non-Destructive Academy of South Africa (NASA)
Research in NDE

Darrell Comins, Wits University. Raman and Brillouin scattering.

Frikkie de Beer, NECSA. Neutron Imaging.

Arthur Every, Wits University. Ultrasonics

Jasson Gryzagaridis, University of Cape Town. Optical methods.

Phillip Loveday, CSIR. Guided wave inspection of railway track.
Introduction - Why Laser Ultrasound?

Laser ultrasound has emerged as a major area of science and technology.

It provides a non-contact and non-destructive means of coupling into ultrasound in solids, and has found a wide range of applications in defect detection, and materials characterization, etc.

It can be applied to irregular geometries, reach restricted areas via optical fibres and probe objects in hostile environments.

It provides high spatial resolution and is suited to the study of microstructures and thin films.

**Disadvantages:** Expensive, complex, and less sensitive and robust as compared with the use of piezoelectric transducers.
Summary

This paper describes three laser-based methods for probing surface acoustic waves (SAW) on solids and thin surface coatings.

- Laser transient grating technique
- Powder detachment method
- Surface Brillouin scattering (SBS)

In the first two techniques a laser pulse is used to excite SAW, while in the third a cw laser is merely used to probe thermal SAW fluctuations in the surface profile of a sample.

Results from the author's research will be provided as illustrations.
Lasers used to probe materials with ultrasonic signals

Much as seismologists analyze the Earth’s structure using seismic waves from explosive detonations, Cornell researchers are probing materials in the laboratory by pinging the materials’ surfaces with laser pulses and detecting and analyzing the resulting sound waves.

The researchers say their technique could represent a powerful new tool to probe the structure of a wide range of materials — including metals, semiconductors and composites — and to detect damage and defects in them.

Collaborating on the research are Professor of Theoretical and Applied Mechanics Wolfgang Sachse; Visiting Professor Arthur Every of the University of Witwatersrand, South Africa; Senior Research Associate Kwang-Kul Kim and Associate Professor of Materials Science and Engineering Michael Thompson.

The researchers are now publishing their results in scientific journals and discussing them at conferences. They first reported application of the technique to silicon in the Sept. 17 issue of Physical Review Letters and have in press five additional papers detailing the technique.

To date, their work has focused on single-crystal specimens of silicon and a number of composite materials. Because of composites’ design and layering, they are particularly lightweight and strong — properties that have led to their use in rocket motors and structural components used in aircraft and naval vessels.

However, said Sachse, analysis of composite parts in these applications have been complicated by some of their characteristics. For example, composites may exhibit different mechanical properties when measured in different directions through the material — called anisotropy — and they are often thick and have irregular shapes, all of which make them defy conventional ultrasonic inspection techniques.

“Until now, seeing inside these materials — that is, getting ultrasonic signals in and out of them and extracting structural information from the signals — has been consid-

at a specimen so that its spot is somewhat less than a millimeter across, the sudden heating of the surface causes an expansion of the material. This expansion produces an ultrasonic wave made up of many frequencies. The wave propagates through the material like the wave from a pebble hitting the surface of a pond, and the researchers have used a similar technique called phonon imaging, which is based on very high frequency thermal vibrations, or phonons. These experiments can only be carried out at supercold liquid-helium temperatures to probe the anisotropic structure of small specimens of non-metallic crystals.

However, by using laser-generated ultrasonic beams, the Cornell research team
Bulk and Surface Acoustic Waves (SAW)

**Bulk Waves**

**SAW**

$V_L > V_S > V_R$
Mechanisms for Laser-generation of Ultrasound

Surface thermoelastic source

Buried thermoelastic source

Ablative source

Lateral near-surface thermal stresses

Radial thermal stresses

Reaction force

Ablated material
SAW’s are generated thermo-elastically by crossed laser pulses forming an interference pattern on the sample, the period of which defines the SAW wavelength. The SAW are detected by diffraction of a probe beam.
The laser pulse generates two counter-propagating SAW, which superpose to form a standing SAW. The heterodyne detected scattered light varies with the period of the SAW.

The Fourier spectrum of the acoustic oscillations of the surface is shown in the inset. Two modes are present here, which are the Rayleigh mode and first Sezawa mode (a higher order plate-like guided mode for a supported layer).
Periodically Patterned Thin Film Structures in the Semiconductor Industry

Characterization with SAW

Λ ∼ d   State-of-the-art d = 130 nm
How to model?
SAW Dispersion Relation – Zone Folding for Periodic Structure

\[ \omega / k_x = c_T \]

- PseudoSAW
- SAW’s
- Bulk wave domain/
  Supersonic domain/
  Radiative zone
- Evanescent wave domain/
  Subsonic domain

\( \pi / a, \ a = \text{spatial period} \)
SAW Dispersion for Patterned Structure (Maznev et al.)

SAW dispersion curves (symbols) measured with wavevector (a) along copper bars and (b) perpendicular to the bars, i.e. in the direction of periodicity. Dotted lines correspond to bulk wave thresholds. Surface modes are “leaky” in the radiative zone above T. Solid lines in (a) were obtained by “effective medium” calculations. Solid lines in (b) correspond to the dispersion curves from (a) re-plotted vs. reduced wavenumber.
Calculated and Measured Dispersion Relation for Propagation Perpendicular to the Bars.

Compact and robust optics head integrated into a fully automated measurement station

Acoustic wavelength range: 2-11 µm
Probe spot size: 30x17 µm
Measurement time: ~1s
SAW frequency range 0.1-1.2 GHz
**Anisotropic Solids**

**Anisotropy:** properties such as wave speed depend on direction. More important types of anisotropic materials:

- **Crystals:** Semiconductors Si, Ge, GaAs, etc., Transducer materials quartz, LiNbO$_3$, etc. Ni-based super-alloys, etc.
- **Polycrystalline textured materials:** Thin protective coatings, etc.
- **Fiber composites:** C-fiber epoxy, glass fibre, etc
- **Fibrous organic materials:** wood, bone, etc
- **Metamaterials:** superlattices, phononic crystals
- **Stressed solids:** elastoacoustic effect
- **Geological strata:** Stratification, tectonic effects
Distinction between phase velocity $v$ and ray (group) velocity $V$

Phase velocity $v = f\lambda = \omega/k =$ velocity of wave fronts

Ray velocity $= \text{grad}_k \omega(k) =$ velocity of wave packet
Ray Focusing Due to Anisotropy

\[ k = \text{wave vector} \]
\[ V = \nabla_k \omega(k) = \text{ray vector} = \text{energy flow vector} \]

Focusing factor \( A = \frac{d\theta_k}{d\phi_V} \propto |K_\omega|^{-1} \)

\[ K_\omega = \text{curvature of } \omega = \text{const. curve} \]

At inflection point \( A = \infty \)
Powder Detachment Method for Observing Laser-generated SAW

- Method developed by Kolomenskii and Maznev.
- Adapted from a technique for cleaning surfaces.
- Fine alumina powder spread of a surface.
- SAW generated by point- or line-focused pulsed laser.
- The high acceleration of the surface in the path of the SAW overcome the van der Waals forces, and the particles are detached from the surface.
- The path of the SA is revealed by clean areas of the surface, and can be photographed.
Surface Phonon Focusing in GaAs

Reflection and Refraction - Tri-refringence

In reflection and refraction at a plane surface/interface there is phase matching of incoming and outgoing waves at the interface. The frequencies must all be the same and so should the component of \( \mathbf{k} \) (\( s \)) in the surface, \( k_\parallel (s_\parallel) \). The sextic slowness equation yields six solutions for \( s_\parallel (k_\parallel) \), real or complex. Only real solutions with outgoing \( \mathbf{V}'s \) (dark solid lines for reflection) or complex having exponential fall-off (evanescent waves, dark dashed lines for reflection) are chosen.

Figure 38.33 A calcite crystal produces a double image because it is a birefringent (double-refracting) material. (Henry Leap and Jim Lehman)
Ray Splitting in the reflection of a SAW at the edge of a (111)-oriented GaAs crystal, (a) observed SAW trace, (b) ray diagram, (c) slowness surface interpretation.

Every and Maznev, JASA 127, 2813 (2010).
Light Scattering by Thermal fluctuations

- Heat resides in the mechanical vibrations (elastic waves) of a solid, which extend in frequency up into the THz range. (In metals there is also thermal energy in the random motion of the conduction electrons, which we do not consider here).

- According to classical thermo-statistical mechanics, the energy residing in any vibrational mode of a solid at a temperature $T$ is on average equal to $k_B T$, where $k_B = 1.38 \times 10^{-23}$ J/K is Boltzmann's constant.

- Thermal vibrations result in fluctuations in the density and hence refractive index of a solid, and also give rise to dynamic corrugations in a nominally flat surface. Light incident on a solid is, as a consequence, weakly but measurably scattered by these fluctuations.

- Light scattering by acoustic waves is a form of Raman scattering known as Brillouin scattering.

- The Fluctuation Dissipation Theorem states that the fluctuations in the displacement field at frequency $\omega$ are related to the corresponding displacement response function (Green's function) by $\langle |u(\omega)|^2 \rangle \propto \frac{T}{\omega} \text{Im} G(\omega)$. Generalization of the idea that an oscillator in a thermal bath will fluctuate at its frequency $\omega$ and also absorb energy if forced at $\omega$. 
Surface Brillouin Scattering (SBS)

In SBS, a cw laser beam is incident on a surface, and the spectrum of the light scattered by thermal fluctuations in the surface profile, corresponding to the ambient temperature, is measured. The conditions for back-scattering from surface corrugations of velocity $v$ are $k_{//} = 2k_i \sin \theta$ and change in frequency of light $\omega = \pm \nu k_{//}$ - surface ripple scattering mechanism. The laser is not exciting the thermal fluctuations, merely probing them. The scattering cross section is given by

$$\frac{d^2 \sigma}{d\Omega d\omega} = \frac{AT}{\omega} \text{Im} G_{33}(k_{//}, \omega)$$

SAW gives rise to sharp line in the spectrum, bulk acoustic waves to a continuum. In transparent materials light is scattered by dynamic fluctuations in the strain field, which cause fluctuations in the refractive index - elasto-optic mechanism. Frequency shifts for bulk wave scattering (up to $\sim 150$ GHz) are much larger than for surface wave scattering (up to $\sim 30$ GHz).
$G_{33}(k_// / \omega)$ for [100] direction in Cu(001) surface

- The response near the Rayleigh wave resonance is like that of a forced, damped harmonic oscillator, with strong dissipation at the resonance frequency.
- The continuum is due to bulk modes impinging on the surface.
Argon ion laser $\lambda = 514.5\,\text{nm}$
Detector: Low noise silicon avalanche diode ($< 1\,\text{c/s}$)
Contrast: $\sim 10^{11}$ obtained by multi-passing

Aerial view - (3+3) pass tandem Fabry-Pérot interferometer
SBS spectrum of $V_{C_{0.75}}$ (Zhang, Comins & Every) The calculated spectrum is proportional to $\text{Im} \, G_{33}(k_{\parallel}, \omega)$.
Slow on Fast Combination: α Si on Si(001). (Zhang, Comins & Every)

Fit to measured dispersion relation for Rayleigh and Sezawa waves

The Si sample has been amorphised to various depths by argon ion bombardment. Comparison is shown between measurement and calculation, fitting the elastic constants of the amorphous layer (C_{11}=138 GPa, C_{44}=48 GPa).
Fast-on-slow Combination – TiN on HSS Steel (Pang, Every, Comins)

**Fit to measured dispersion using adjusted elastic constants of TiN**

At a critical value of $k_h h$, the Rayleigh SAW degenerates into the HSS continuum. For large $k_h h$ the lowest resonance evolves into the Rayleigh wave for TiN.
A Selection of Other Recent Laser-based SAW Investigations

- B B Djordjevic, QNDE2012, *Quantitative ultrasonic guided wave testing of composites*.
- F Hernandez-Valle et al., QNDE2012, *Laser generation and detection for surface wave interaction with different defect geometries*.
- B Sherman and O Balogun, QNDE2012, *Optical generation of high amplitude laser generated surface acoustic waves*.
Thank you for your attention