

Review on Acoustic Transducers for Resonant Ultrasound Spectroscopy

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Determination of elastic constants using resonant ultrasound spectroscopy requires transducers that can measure resonance frequencies accurately and identify the vibrational mode of each resonance frequency. We developed three transducers, namely an electromagnetic acoustic transducer, a tripod piezoelectric transducer coupled with a laser Doppler interferometer, and an antenna transmission transducer, for use with various materials and in different measurement circumstances. Their capability in resonant ultrasound spectroscopy and their applications are described.

INTRODUCTION

Resonant ultrasound spectroscopy (RUS)^{1–4} is nowadays recognized as a powerful method for measuring elastic constants of solids. An advantage of RUS over other methods is that all the independent elastic constants are determined from a single specimen by a single resonance spectrum measurement. This feature is especially advantageous for studying materials with low crystallographic symmetry, for which the number of independent elastic constants increases. To determine all the independent elastic constants using conventional acoustic techniques, many specimens with different crystallographic orientations are needed, for which acoustic velocities in different crystallographic directions and polarizations have to be measured. This therefore becomes a time-consuming task, especially for measurements at high/low temperatures, because a heating/cooling process has to be carried out for each measurement. In addition, for small volumes of material, preparation of specimens with different crystallographic orientations is difficult. On the other hand, RUS uses the resonance frequencies of mechanical free vibration, and all independent elastic constants are determined simultaneously from the resonance frequencies, requiring only a single specimen. As a result, the method shows higher accuracy and has contributed to the study of elastic properties of solids.^{5–14}

When acoustic methods including RUS are used, elastic constants are determined from the sound velocity (or resonance frequency), dimensions, and

mass density. Then, in addition to accurate measurement of sound velocity and resonance frequency, mode identification is key to obtaining reliable elastic constants. The sound velocity and resonance frequency are determined from a combination of independent elastic constants. The contribution of each elastic constant to the sound velocity and resonance frequency is different for each vibrational mode; For example, the sound velocities of longitudinal and shear waves are governed by the longitudinal and shear components of the elastic constants, respectively. The pulse-echo method then determines elastic constants by measuring longitudinal and shear waves independently. On the other hand, in RUS, many resonance frequencies are measured simultaneously, making mode identification problematic. The resonance vibrations of a rectangular parallelepiped specimen can be classified into several groups depending on the symmetry of the vibrational displacements,¹⁵ with all resonance vibrations being labeled as a fundamental or harmonic mode of a group. Numerically, the resonance frequencies are calculated by the Ritz method using the elastic constants, mass density, and dimensions.^{2,3} When a set of elastic constants that are close to the true set is known, a vibrational mode can be identified by comparison between the measured and calculated resonance frequencies. However, when reliable initial elastic constants are not given, mode identification by such comparison becomes difficult, and misidentification can occur, leading to unreliable elastic constants. Therefore, mode identification is a key issue, especially for newly developed materials.

To solve this problem, there are two approaches: (i) development of transducers that can measure only intended modes, and (ii) development of new mode identification methods. In RUS, resonance frequencies are commonly measured using piezoelectric transducers.^{2,3,16} A specimen is held between two piezoelectric transducers, one of which is used to excite the specimen while the other detects the oscillation amplitude. By sweeping the frequency of the driving signal, the resonance spectrum is obtained. The magnetostrictive effect, in which a rectangular parallelepiped sample is coated with a thin film of magnetostrictive material¹⁷ and laser ultrasonics are also available.^{18,19} With such transducers, most of the resonance vibrations are excited and mode identification is not straightforward.

In the following, we describe three transducers, namely an electromagnetic acoustic transducer, a tripod piezoelectric transducer coupled with a laser Doppler interferometer, and an antenna, that were developed for RUS with various materials and in different measurement circumstances, the first two possessing mode identification capability.

MODE-SELECTIVE ELECTROMAGNETIC ACOUSTIC RESONANCE

An electromagnetic acoustic transducer (EMAT)^{20–23} is a noncontact acoustic transducer for conductive and ferromagnetic materials, being used for nondestructive evaluation of structures. A typical EMAT consists of permanent magnets and conductive wires, and a tone-burst signal is applied to the coil to operate it. When an EMAT is placed close to the surface of a conductive material, an eddy current is generated on the specimen surface, and the interaction between the eddy current and the static magnetic field generated by the permanent magnets excites the Lorentz force, which excites acoustic waves. In ferromagnetic materials, the oscillating magnetic field generated by the coil excites acoustic waves through the magnetostriction effect.

An EMAT requires no coupling agent for measurement, and the lack of contact between the specimen and EMAT enables accurate measurement of the acoustic velocity, resonance frequency, and attenuation coefficient. This feature is indispensable for accurate measurement of elastic constants. However, the most important feature is its mode selectivity. The configuration of an EMAT is generally designed by changing the shape of the magnets and coils for particular purposes so that a desired acoustic wave is excited; bulk waves, surface waves, and guided waves can be selectively excited.^{24–26} Regarding the resonance vibration of a rectangular parallelepiped specimen, an EMAT configuration consisting of a solenoid coil and permanent magnets has been developed,²⁷ using which the resonance frequencies belonging to a specific

group can be selectively measured. Figure 1 shows a schematic of such an EMAT. The specimen is inserted into a solenoid coil, and a static magnetic field is applied using the permanent magnets, causing a Lorentz force on the specimen surfaces. By changing the relative direction of the magnetic field and the axial direction of the coil to the specimen, resonance vibrations belonging to a specific group can be selectively measured. Figure 2 shows the resonance spectra measured using a piezoelectric transducer and an EMAT for Ti-6Al-4V alloy reinforced with continuous SCS-6 SiC fibers.²⁸ In the spectrum measured using the piezoelectric transducer, there are many resonance peaks. However, in the resonance spectra measured with the EMAT, a smaller number of peaks appear, and by changing the configuration of the EMAT, only a specific group is excited, which is helpful for mode identification. A_g , B_{2g} , and B_{3g} groups¹⁵ in Fig. 2 represent breathing vibration and torsional vibration about x_2 and x_1 axis, respectively, where the x_1 , x_2 , and x_3 axes are defined parallel to the edges of the rectangular parallelepiped specimen. Acoustic spectroscopy coupled with an EMAT is called electromagnetic acoustic resonance (EMAR).²⁹

An EMAT is advantageous for measurements at high temperatures as well as for mode identification. Typical piezoelectric transducers are not usable above the Curie temperature, and improvement of transducers is required for measurement at high temperatures. On the other hand, an EMAT is applicable even at above 1300 K when using a high-melting-point material, e.g., Ni alloy, for the coil. In the general measurement setup, the heater, thermocouple, and solenoid coil are placed in a vacuum chamber, and the static magnetic field is applied from outside. Figure 3 shows the evolution of the resonance frequencies at high temperatures for Ti monocrystal measured using an EMAT.³⁰ By changing the direction of the magnetic field, resonance frequencies in two groups are measured during one heating sequence, and elastic constants

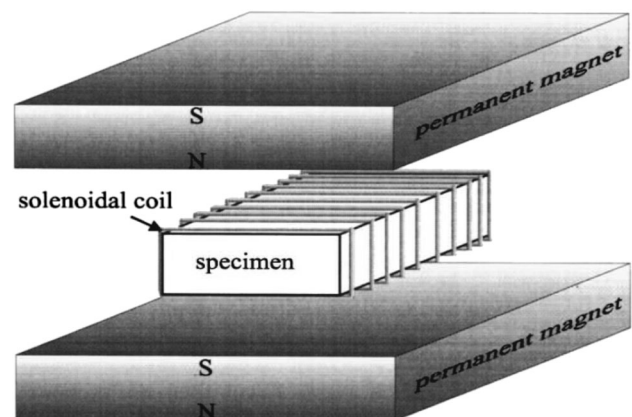


Fig. 1. Typical setup for electromagnetic acoustic transduction. Reprinted with permission from Ref. 27. Copyright 1999, Acoustic Society of America.

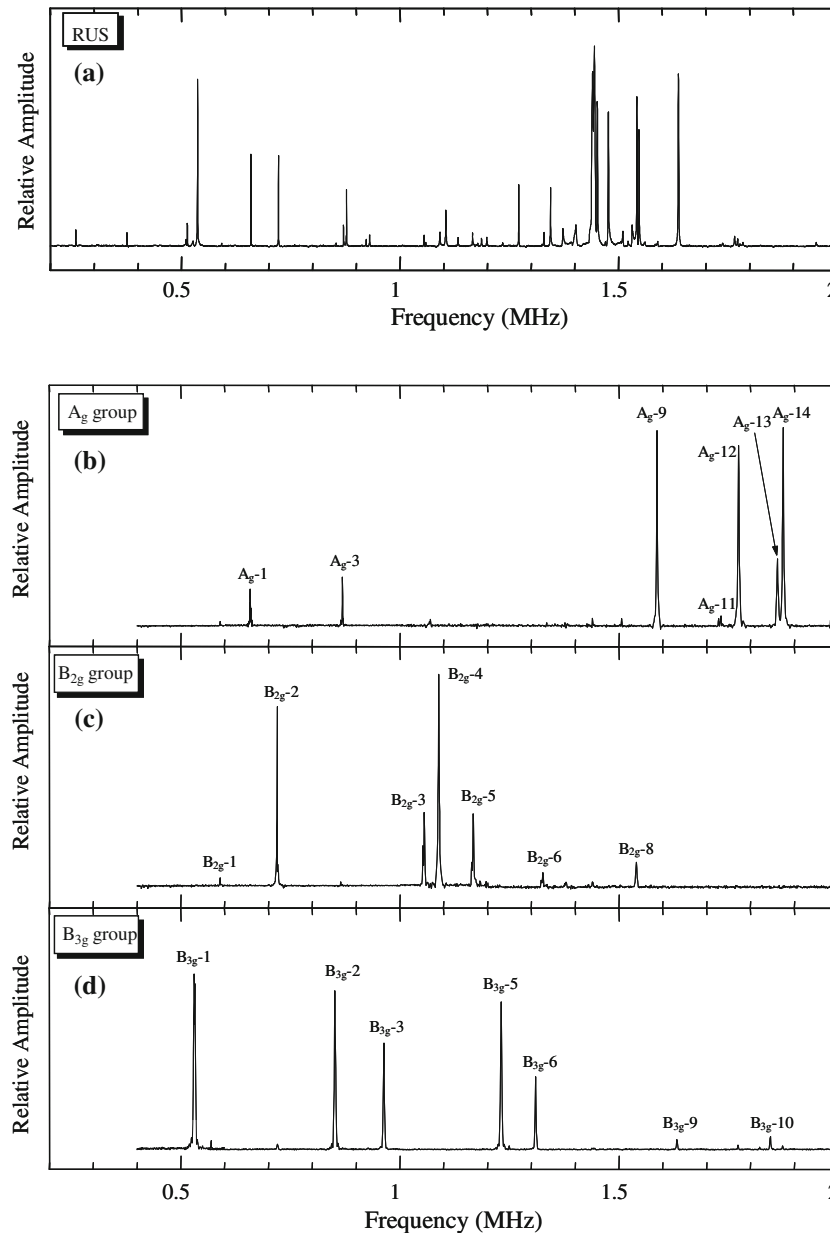


Fig. 2. Resonance spectra of Ti-6Al-4V alloy reinforced with continuous SCS-6 SiC fibers, measured using (a) a conventional piezoelectric transducer and (b), (c) an EMAT with different configurations for (b) A_g , (c) B_{2g} , and (d) B_{3g} group. Reprinted from Ref. 28. Copyright 1999, with permission from Elsevier.

are determined. Using this setup, resonance frequencies are measurable up to 1323 K through the hcp–bcc phase transformation. Below the phase-transformation temperature (dashed line in Fig. 3), resonance frequencies in A_g and B_{3g} groups are identified. Around the phase-transformation temperature, a jump of resonance frequency occurs, and there is ambiguity in the mode identification. However, resonance frequencies are measurable below 1323 K. The system has been used to determine elastic constants of titanium alloy unidirectionally reinforced with SiC fibers,³¹ monocrystal and polycrystalline titanium,³⁰ monocrystal α -Fe,³² and FePt alloy³³ at high temperatures.

TRIPOD NEEDLE TRANSDUCER AND MODE IDENTIFICATION BY LASER DOPPLER INTERFEROMETRY

Piezoelectric transducers are superior in the sense that they are applicable to any kinds of solid; resonance frequencies are measurable just by holding the specimen. However, all vibrational modes appear in the resulting resonance spectra, as shown in Fig. 2. This makes mode identification complicated, especially for lower-symmetric materials, which had been a long-running problem in RUS. To solve this problem, we developed a measurement setup consisting of tripod piezoelectric

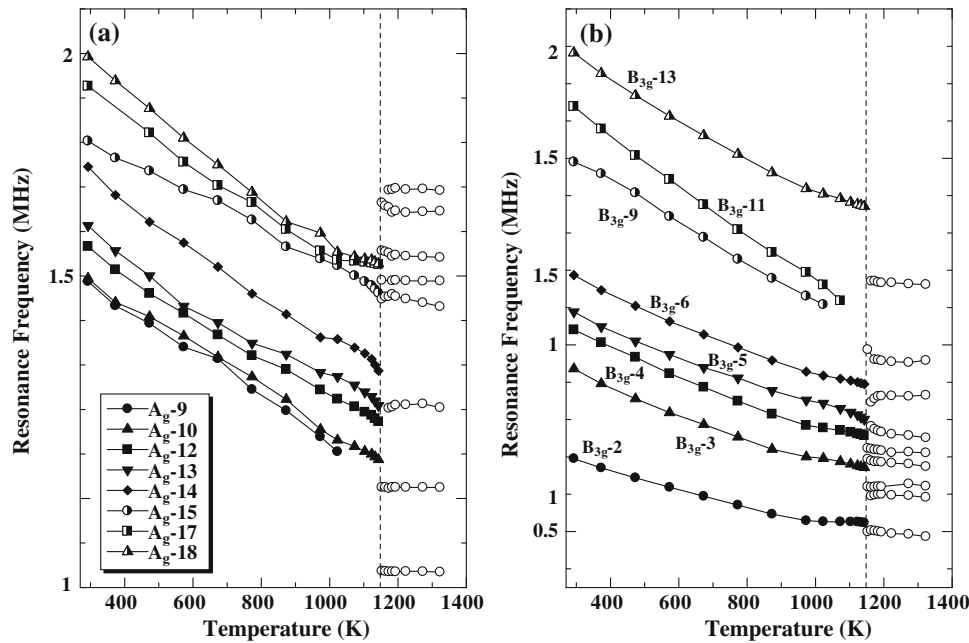


Fig. 3. Change of resonance frequencies of A_g modes (a) and B_{3g} modes (b) with increasing temperature in monocrystal Ti. Reprinted from Ref. 30. Copyright 2004, with permission from Elsevier.

pinducers and a laser Doppler interferometer.³⁴ The tripod transducer consists of two piezoelectric pinducers, as transmitter and receiver, and a supporting needle (Fig. 4). The specimen is placed on the transducer set with no external force applied except for the specimen's weight. When resonance frequencies are measured in vacuum and at constant temperature, the difference of resonance frequencies among three independent measurements is less than 0.001% for rectangular parallelepiped α -quartz.³⁵

The tripod transducer is convenient for optical measurements, because there are no objects above the specimen, enabling its combination with displacement measurement using a laser Doppler interferometer. Each resonance frequency possesses a unique displacement distribution that can be computed using the Ritz method.³⁴ Therefore, by visualizing the displacement distribution, mode identification becomes possible. For this purpose, the system shown in Fig. 4 was developed. The system measures the distribution of normal displacement at the upper surface by scanning a laser Doppler interferometer. Figure 5 shows the displacement distributions measured and computed on a surface of polycrystalline aluminum alloy, measuring $11.92 \times 10.93 \times 9.86 \text{ mm}^3$.³⁴ Dark area indicates nodal region, and bright area antinodal region. They show good agreement, indicating that mode identification is performed without ambiguity. For transparent materials, resonance frequencies are measured first, then metallic film is deposited on a surface as a mirror to measure the displacement patterns. The deposition changes the resonance frequencies, but this effect is so small that mode identification is hardly affected. This

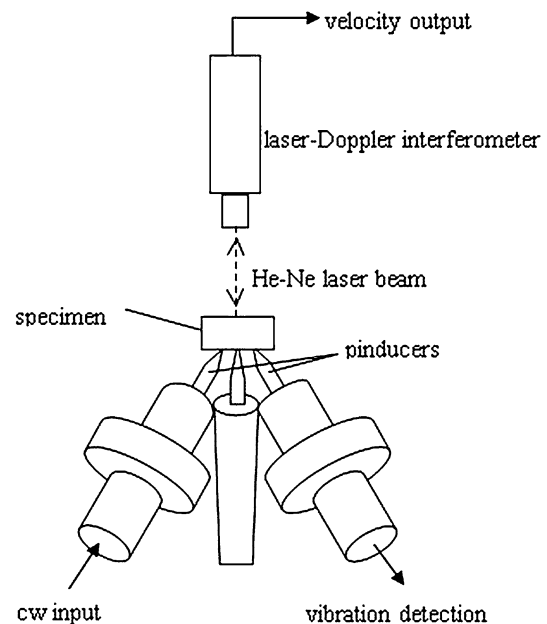


Fig. 4. RUS/laser measurement setup. Reprinted with permission from Ref. 34. Copyright 2002, Acoustic Society of America.

setup is applicable to several kinds of material at room temperature.

An example where mode identification using the present setup plays an important role is described here. RUS is applicable to layered materials,³⁶ and the elastic constants of a thin film deposited on a substrate are also measurable. In such a measurement, the elastic constants of the substrate are determined before the deposition, and the elastic constants of the thin film are determined from the

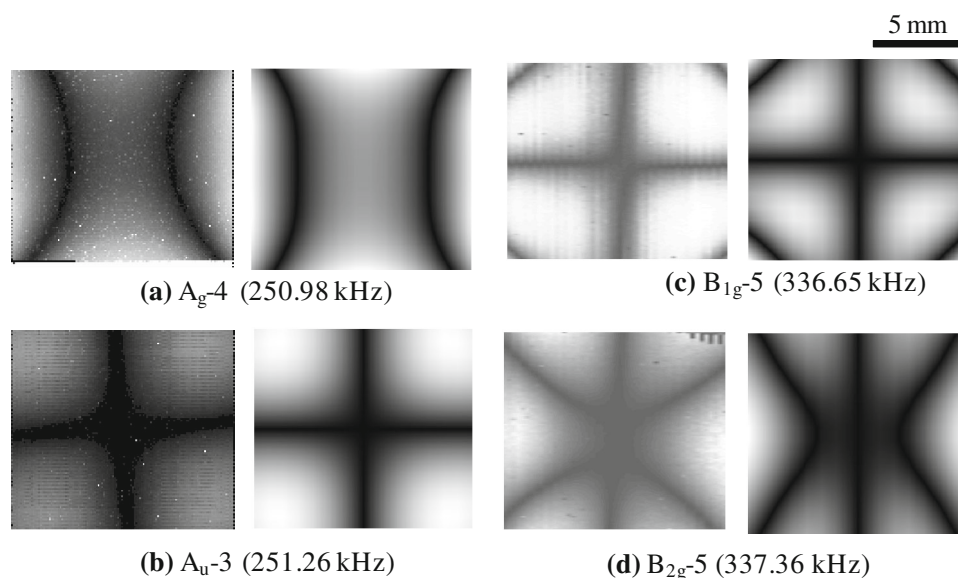


Fig. 5. Comparison of the measured (left) and computed (right) distribution of normal displacement amplitude for a surface, measuring $11.92 \times 10.93 \text{ mm}^2$, of an aluminum alloy rectangular parallelepiped: (a) A_g-4 , (b) A_u-3 , (c) $B_{1g}-5$, and (d) $B_{2g}-5$ mode. Reprinted with permission from Ref. 34. Copyright 2002, Acoustic Society of America.

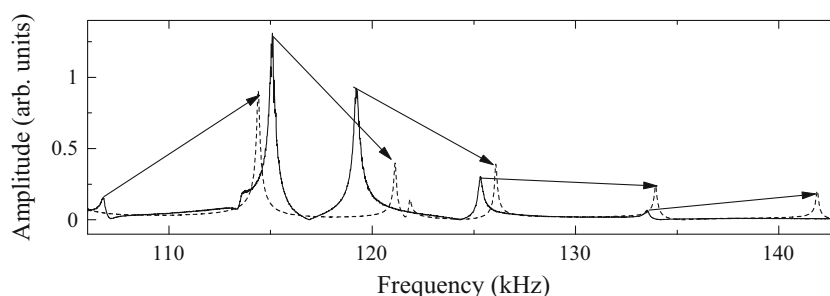


Fig. 6. Resonance spectra of silicon substrate (solid line) and 3.8- μm -thick diamond/silicon layered specimen (dashed line). Reprinted from Ref. 11. Copyright 2004, with permission from Elsevier.

resonance frequencies measured after deposition. The film thickness is significantly smaller than the substrate thickness in many cases, and resonance frequencies measured after deposition appear close to the corresponding resonance frequency measured before deposition. However, when thicker or stiffer film is deposited, the changes in the resonance frequencies become larger, and mode identification becomes quite difficult; the elastic constants of thin films are often different from those of corresponding bulk materials because of the larger volume of defective structures introduced during deposition,³⁷ and the frequency shift caused by deposition cannot be estimated reliably. An example is shown in Fig. 6, in which the resonance spectra of a 0.5-mm-thick Si substrate before and after deposition of a 3.8- μm -thick diamond film are shown. Apparently, the frequency shifts caused by deposition are small, but after mode identification using the laser Doppler interferometer, it was revealed that the frequency shift was more than 5%, as indicated by arrows.

ANTENNA TRANSMISSION ACOUSTIC RESONANCE

Resonance vibrations can be excited in piezoelectric materials via the piezoelectric effect, being applicable to RUS. In piezoelectric oscillators, electrodes are fabricated on piezoelectric materials to apply an electric field. The electrodes are useful for exciting desired acoustic waves efficiently. However, this approach is not suitable for RUS, because the deposition of the electrodes changes the electrical boundary conditions as well as the mass and elastic constants on the surface, making the analysis of the resonance vibrations complicated. We thus propose the use of an antenna for electrodeless measurement.³⁸ The antenna simply consists of three conductive wires, acting as an input, output, and ground, embedded in a nylon base; resonance vibrations are excited using the electric field generated by the antenna placed close to the specimen. Using the antenna, the resonance fre-

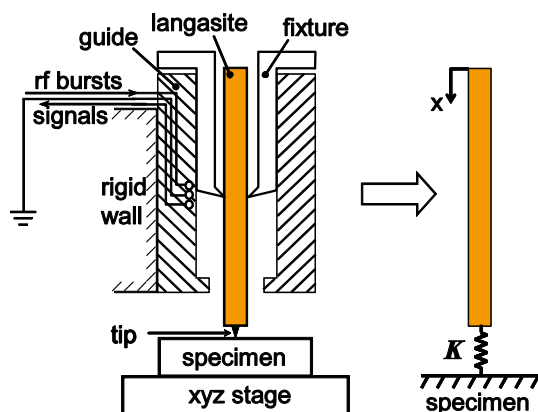


Fig. 7. Schematic of the langasite probe with a diamond tip (left), and the vibrational model with a contact spring representing the contact stiffness K between the tip and specimen (right). Reprinted with permission from Ref. 45. Copyright 2008, AIP Publishing LLC.

quency is measurable by just putting a piezoelectric specimen on the antenna. Except for the specimen's weight, no external force is applied. Similar to EMAR, the antenna is applicable for measurement at high temperatures when using high-melting-temperature material,³⁹ with the highest measurable temperature being the Curie temperature of the specimen. We call RUS combined with the antenna, antenna transmission acoustic resonance (ATAR).

One of the applications of ATAR is in a local stiffness measurement system. When an oscillator vibrating at a resonance frequency contacts with a solid, the resonance frequency increases. The ratio of the change depends on the stiffness of the solid, and by achieving point contact, local stiffness measurements can be performed. Dynamic-mode atomic force microscopy (AFM) is a typical example of this, where the resonance frequency of bending modes of the AFM cantilever is measured, determining the local stiffness at the cantilever contact.^{40,41} In this method, the oscillator is not isolated, and there are ambiguous parameters such as the elasticity of the gripping wall and the variable biasing force for contact, making quantitative measurements difficult. In ATAR, an isolated oscillator is fabricated, and quantitative measurements are achieved, being called resonant ultrasound microscopy (RUM).^{42–46}

In RUM, a rectangular-rod langasite oscillator is used. The oscillator is held at the center in the length direction, and is oscillated using the antenna as shown in Fig. 7.⁴⁵ When the fundamental mode of the longitudinal vibration in the length direction is excited, the center of the oscillator becomes a nodal point. Therefore, holding the oscillator at the center region hardly affects the resonance frequency, because the oscillator is acoustically isolated. Then, the resonance vibration is not affected by the surrounding conditions except for the stiffness where the tip is in contact. The oscillator is allowed to move in the vertical direction, and the contact force

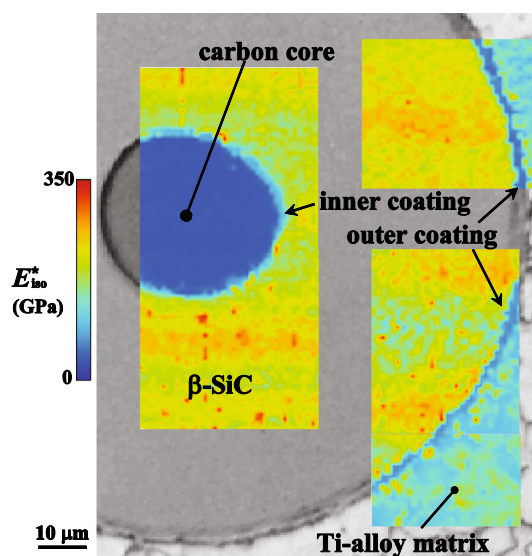


Fig. 8. Effective Young's modulus mapping images on a single embedded SiC fiber overlaid on an optical microscopy image. Reprinted with permission from Ref. 45. Copyright 2008, AIP Publishing LLC.

is unchanged. Figure 8 shows effective Young's modulus mapping on a cross-section of a silicon carbide fiber embedded in a Ti alloy matrix.⁴⁵ The spatial resolution of the present RUM system is approximately 200 nm, and the effective Young's modulus of the inner ($\sim 1.5 \mu\text{m}$ thick) and outer ($\sim 3 \mu\text{m}$ thick) carbon coating was successfully obtained. The spatial resolution of RUM is lower than that of dynamic-mode AFM, but its quantitative capability is an important characteristic that dynamic-mode AFM does not have. Because of the simple configuration of the oscillating system, a ballpoint-pen probe was recently developed.⁴⁶

The use of the antenna is advantageous for small piezoelectric specimens, because the resonance spectrum can be measured just by putting the specimen on it. This approach is free from the holding problem, and the resonance spectrum of a quartz substrate, measuring $2.5 \times 1.7 \times 0.01 \text{ mm}^3$, has been measured. This ability to measure small specimens drastically improves the sensitivity of a quartz-crystal microbalance (QCM) for biomarker sensing. A QCM measures the mass of atoms and molecules attached to a quartz surface based on the decrement ratio of the resonance frequency, being used for evaluating affinity between biomolecules. According to Sauerbrey's equation,⁴⁷ the sensitivity of such a microbalance based on the decrement ratio of the resonance frequency per unit mass is inversely proportional to the square of the quartz thickness. Thinning the oscillator, therefore, contributes to improvement of the sensitivity. However, in a conventional QCM, Au electrodes are attached onto the quartz surface and cannot be removed. The relative increment due to the mass of the electrodes prevents further sensitivity improvement as the

quartz becomes thinner. This problem was solved by using the antenna, and the resulting wireless-electrodeless quartz crystal microbalance (WE-QCM) showed drastically improved sensitivity.⁴⁸

CONCLUSION

The features of three transducers developed for RUS are described herein. The tripod transducer coupled with a laser Doppler interferometer is suitable for measurement of the elastic constants of any solid at room temperature. At high/low temperatures, an EMAT is applicable for conductive and/or ferromagnetic materials, and the antenna for piezoelectric materials. The antenna approach does not require attachment of electrodes to the piezoelectric materials for excitation or detection of resonance vibrations. This feature is useful not only for measurement of elastic constants by RUS but also for improvement of piezoelectric devices.

REFERENCES

1. H.H. Demarest Jr, *J. Acoust. Soc. Am.* 49, 768–775 (1971).
2. I. Ohno, *J. Phys. Earth* 24, 355–379 (1976).
3. A. Migliori, J.L. Sarrao, W.M. Visscher, T.M. Bell, M. Lei, Z. Fisk, and R.G. Leisure, *Physica B* 183, 1–24 (1993).
4. J. Maynard, *Phys. Today* 49, 26–31 (1996).
5. I. Ohno, *Phys. Chem. Miner.* 17, 371–378 (1990).
6. H. Ledbetter, C. Fortunko, and P. Heyliger, *J. Mater. Res.* 10, 1352–1353 (1995).
7. H. Ledbetter, C. Fortunko, and P. Heyliger, *J. Appl. Phys.* 78, 1542–1546 (1995).
8. H. Ogi, G. Shimoike, M. Hirao, K. Takashima, and Y. Higo, *J. Appl. Phys.* 91, 4857–4862 (2002).
9. J.H. So, J.R. Gladden, Y.F. Hu, J.D. Maynard, and Q. Li, *Phys. Rev. Lett.* 90, 036103 (2003).
10. H. Ogi, N. Nakamura, K. Sato, M. Hirao, and S. Uda, *IEEE Trans. Ultrason. Ferroelect. Freq. Contr.* 50, 553–560 (2003).
11. N. Nakamura, H. Ogi, and M. Hirao, *Acta Mater.* 52, 765–771 (2004).
12. Y. Suzuki, V.R. Fanelli, J.B. Betts, F.J. Freibert, C.H. Mielke, J.N. Mitchell, M. Ramos, T.A. Saleh, and A. Migliori, *Phys. Rev. B* 84, 064105 (2011).
13. N. Nakamura, H. Ogi, and M. Hirao, *J. Appl. Phys.* 111, 013509 (2012).
14. R. Tarumi, H. Ledbetter, H. Ogi, and M. Hirao, *Philos. Mag.* 93, 4532–4543 (2013).
15. E. Mochizuki, *J. Phys. Earth* 35, 159–170 (1987).
16. J.D. Maynard, *J. Acoust. Soc. Am.* 91, 1754–1762 (1992).
17. V.T. Kuokkala and R.B. Schwarz, *Rev. Sci. Instrum.* 63, 3136–3142 (1992).
18. P. Sedlak, M. Landa, H. Seiner, L. Bicanova, and L. Heller, in *Proceedings of the 1st International Symposium on Laser Ultrasonics: Science, Technology and Applications*, Montreal, Canada, 16–18 July, 2008.
19. D.H. Hurley, S.J. Reese, S.K. Park, Z. Utegulov, J.R. Kennedy, and K.L. Telschow, *J. Appl. Phys.* 107, 063510 (2010).
20. R.B. Thompson, *IEEE Trans. Sonics Ultrason.* SU-25, 7–15 (1978).
21. G.A. Alers and D.T. MacLauchlan, *Review of Progress in Quantitative Nondestructive Evaluation*, Vol. 2A, ed. D.O. Thompson and D.E. Chimenti (New York: Plenum, 1982), pp. 271–281.
22. W.B. Maxfield and C.M. Fortunko, *Mater. Eval.* 41, 1399–1408 (1983).
23. K. Kawashima, *IEEE Trans. Sonics Ultrason.* 32, 514–522 (1985).
24. R.B. Thompson, *Physical Acoustics*, Vol. 19, ed. R.N. Thurston and A.D. Pierce (New York: Academic, 1990), p. 157.
25. C.F. Vasilie and R.B. Thompson, *J. Appl. Phys.* 50, 2583–2588 (1979).
26. Nurmalia, N. Nakamura, H. Ogi, and M. Hirao, *Jpn. J. Appl. Phys.* 52, 07HC14 (2013).
27. H. Ogi, H. Ledbetter, S. Kim, and M. Hirao, *J. Acoust. Soc. Am.* 106, 660–665 (1999).
28. H. Ogi, K. Takashima, H. Ledbetter, M.L. Dunn, G. Shimoike, M. Hirao, and P. Bowen, *Acta Mater.* 47, 2787–2796 (1999).
29. M. Hirao and H. Ogi, *EMATs for Science and Industry* (Boston: Kluwer, 2003).
30. H. Ogi, S. Kai, H. Ledbetter, R. Tarumi, M. Hirao, and K. Takashima, *Acta Mater.* 52, 2075–2080 (2004).
31. H. Ogi, S. Kai, T. Ichitsubo, M. Hirao, and K. Takashima, *Phil. Mag. A* 83, 503–512 (2002).
32. R. Tarumi, K. Shiraishi, and M. Hirao, *ISIJ Int.* 49, 1432–1435 (2009).
33. N. Nakamura, N. Yoshimura, H. Ogi, and M. Hirao, *J. Appl. Phys.* 114, 093506 (2013).
34. H. Ogi, K. Sato, T. Asada, and M. Hirao, *J. Acoust. Soc. Am.* 112, 2553–2557 (2002).
35. H. Ogi, T. Ohmori, N. Nakamura, and M. Hirao, *J. Appl. Phys.* 100, 053511 (2006).
36. P. Heyliger, *J. Acoust. Soc. Am.* 107, 1235–1245 (2000).
37. N. Nakamura, H. Ogi, T. Shagawa, and M. Hirao, *Appl. Phys. Lett.* 92, 141901 (2008).
38. H. Ogi, K. Motohisa, T. Matsumoto, K. Hatanaka, and M. Hirao, *Anal. Chem.* 78, 6903–6909 (2006).
39. N. Nakamura, M. Sakamoto, H. Ogi, and M. Hirao, *Rev. Sci. Instrum.* 83, 073901 (2012).
40. U. Rabe, J. Turner, and W. Arnold, *Appl. Phys. A* 66, S277–S282 (1998).
41. K. Yamanaka and S. Nakano, *Appl. Phys. A* 66, S313–S317 (1998).
42. H. Ogi, J. Tian, T. Tada, and M. Hirao, *Appl. Phys. Lett.* 83, 464–466 (2003).
43. H. Ogi, M. Hirao, T. Tada, and J. Tian, *Phys. Rev. B* 73, 174107 (2006).
44. J. Tian, H. Ogi, T. Tada, and M. Hirao, *IEEE Trans. Ultrason. Ferroelect. Freq. Contr.* 55, 499–502 (2008).
45. H. Ogi, T. Inoue, H. Nagai, and M. Hirao, *Rev. Sci. Instrum.* 79, 053701 (2008).
46. H. Ogi, Y. Sakamoto, and M. Hirao, *Ultrasonics* 54, 1963–1966 (2014).
47. G. Sauerbrey, *Z. Physik* 155, 206–222 (1959).
48. H. Ogi, *Proc. Jpn. Acad. Ser. B* 89, 401–417 (2013).

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