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Elastic Constants and Debye Temperature of TiC Using a New Ultrasonic Coherent Pulse/cw Technique

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A new simple but sensitive ultrasonic velocity measurement technique, using a coherent pulse/cw system, is described. The technique can readily be used for velocity measurements in either small or large samples, and does not require elaborate instrumentation. This technique has been used to measure the velocities of all three pure acoustic modes along a (110) direction of a single crystal of TiC. These velocities were then used to calculate the elastic constants and the Debye temperature for this sample. The measured velocities are $v_L=9.230\times10^5$ cm sec^{-1}, $v_{T_1}=6.425\times10^5$ cm sec^{-1}, and $v_{T_2}=5.927\times10^5$ cm sec^{-1}. The calculated elastic constants are $c_{11}=3.891\times10^{12}$ dyn cm^{-2}, $c_{12}=0.433\times10^{12}$ dyn cm^{-2}, $c_{44}=2.032\times10^{12}$ dyn cm^{-2}, and the room temperature Debye temperature is 935°K.

1. INTRODUCTION

TWO fairly recent comprehensive papers[1,2] have reviewed ultrasonic velocity measurement techniques employing either pulse or continuous wave (cw) techniques. The purpose of the present paper is to describe a technique which combines both methods, yet retains most advantages of each. Brief descriptions of the pulse echo and cw techniques are given in Secs. 2 and 3, respectively, to provide the background necessary to understand the coherent pulse/cw system described in Sec. 4. The instrumentation required for the new technique is described in Sec. 5. The relationship between acoustic velocities, elastic constants, and Debye temperature for cubic crystals is briefly reviewed in Sec. 6. The application of this technique to the measurement of the elastic constants and Debye temperature of a single crystal of titanium carbide is given in Sec. 7. A brief discussion of the advantages of this technique over other techniques is presented in Sec. 8. An Appendix is added giving the curves of intersection in the [x-y] and [110] planes of the velocity surface of TiC.

2. PULSE ECHO TECHNIQUE

The conventional ultrasonic pulse echo technique operates in the manner indicated in Fig. 1. A short burst of radio frequency electromagnetic energy (pulse) is applied to one side of a piezoelectric transducer which is acoustically bonded to one face of the sample material being studied. The rf electromagnetic pulse is converted by the piezoelectric transducer into mechanical energy which propagates in the sample at a velocity characteristic of the material. If the sample has been prepared in such a way that it has a second face parallel to and directly opposite the first face the mechanical pulse will echo back and forth between these two surfaces until all the mechanical energy has been dissipated in the sample. Each time the pulse returns to the first surface a small amount of the mechanical energy is converted by the piezoelectric transducer into electromagnetic energy, which is amplified and displayed on a cathode ray tube. The complete echo train appears as a series of evenly spaced pulses which decrease with time in an exponential manner.

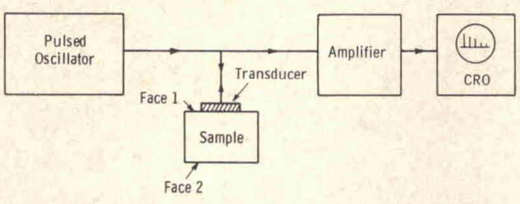

FIG. 1. Simplified block diagram of pulse echo system.

3. cw TECHNIQUE

The cw technique developed by Bolef and Menes[3,4] is operated by setting up mechanical standing waves in a composite oscillator, consisting of a piezoelectric transducer, an acoustic bond, and a sample identical to those employed in the pulse echo technique. A simplified block diagram of this system is shown in Fig. 2. The frequency ν of the Q-meter is adjusted so that a mechanical standing wave pattern near the resonant frequency ν_T of the transducer is generated in the composite oscillator. At this frequency a sharp minimum in the Q-meter reading is obtained.[4] The number of half wavelengths n of the mechanical standing wave system at this frequency ν_n is determined by the length ℓ_S of the sample and the velocity v_S of sound in the sample. The frequency of the Q-meter is next varied to obtain the frequencies $\nu_{(n-1)}$, $\nu_{(n-2)}$, $\ldots$ $\nu_{(n-m)}$, $\nu_{(n+1)}$, $\nu_{(n+2)}$, $\ldots$ $\nu_{(n+p)}$ for which there are

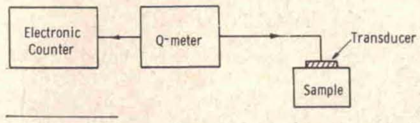

FIG. 2. Simplified block diagram of cw system.

[1] H. J. McSkimin, J. Acoust. Soc. Am. **33**, 606 (1961).
[2] D. I. Bolef and J. de Klerk, IEEE Trans. **UE-10**, 20 (1963).
[3] D. I. Bolef and M. Menes, Phys. Rev. **114**, 1441 (1959).
[4] D. I. Bolef and M. Menes, J. Appl. Phys. **31**, 1010 (1960).

respectively $(n-1)$, $(n-2)$, . . . $(n-m)$, $(n+1)$, . . . $(n+p)$ half-wavelengths in the mechanical standing wave system. If the mechanical Q for each of $(n-m)$ . . . $(n+p)$ mechanical resonances was calculated and plotted as a function of the standing wavenumber n, the plot shown in Fig. 3 would result. The average difference in frequency between two successive resonances, $\Delta\nu_{av}$, can be used to calculate the velocity of sound in the sample according to the formulae[2]

$$v=2\ell_S\Delta\nu_{av}(1+m_T/m_S), \tag{1}$$

or, more accurately, by

$$v=(2\ell_S/n)[\nu_n-(m_T/m_S)(\nu_T-\nu_n)], \tag{2}$$

where m_T and m_S are, respectively, the specific masses of transducer and specimen, ν_T is the resonant frequency of the transducer, and n is given by

$$n=[\nu_n/\Delta\nu_{av}][1-m_T/m_S]. \tag{3}$$

The most precise method of measuring ν_T has been developed by Breslow.[5] Briefly, this method uses a conventional pulse echo system[6] and a gated spectrum analyzer for determining the center frequency of successive echoes. When the driving frequency is below the resonant frequency ν_T, the center frequency of successive echoes increases until ν_T is reached and then remains constant. Likewise, when the driving frequency is greater than ν_T, the center frequency of successive echoes decreases until ν_T is reached and then remains constant. The value of ν_T required in Eq. (2) can be determined by tuning the transmitter until the center frequency of all the echoes, as determined by the spectrum analyzer, is the same. The frequency of the variable frequency oscillator (VFO) or

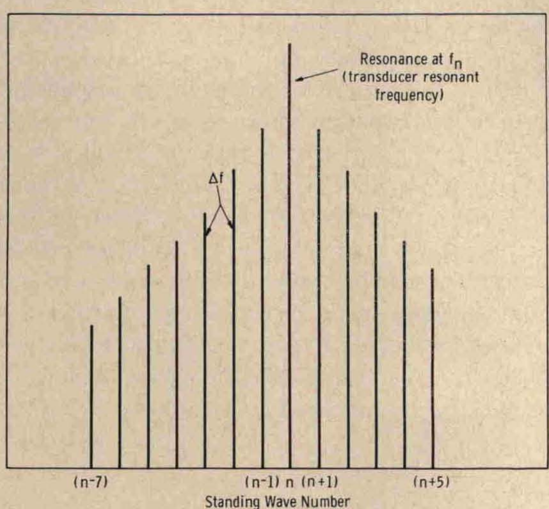

FIG. 3. Plot of mechanical Q vs standing wave number.

[5] D. H. Breslow, Report WAL 143/14-48 for Watertown Arsenal Contract DA-19-020-505-ORD-3882 (August 1956).
[6] B. Chick, G. Anderson, and R. Truell, J. Acoust. Soc. Am. 32, 186 (1960).

TABLE I. Frequency data for standing waves using v_L, v_{T_1}, and v_{T_2} modes.

Parameter	Propagation along [1$\bar{1}$0] for mode v_L	v_{T_1}	v_{T_2}
ν_n(Mc)	8.312566	8.203765	8.107342
$\Delta\nu_{av}$(Mc)	0.574014	0.403986	0.372672
ν_T(Mc)	7.903	7.987	7.987
Standing wavenumber n	14	20	21

transmitter is then measured by means of an electronic counter. The value of ν_T shown in Table I was not determined by the Breslow technique, but estimated from careful measurements of thickness of quartz, evaporated gold electrode, and bond, as a gated spectrum analyzer was not available.

4. COHERENT PULSE/cw TECHNIQUE

The cw system just described has the virtue of using the minimum of instrumentation, viz., only a Q-meter and an electronic counter. However, the correct operation of the Q-meter requires a great deal of patience and skill in obtaining accurate values of ν_n. It has been found possible to overcome this disadvantage by combining the pulse echo and cw techniques in the manner indicated in Fig. 4. If the variable rf attenuator and its connection to the matching network are disregarded, it will be seen that the remainder of the block diagram represents a conventional pulse echo system. The rf pulses are generated by coupling the output of a cw oscillator to a gated power amplifier instead of by the more frequently used self-excited oscillator.[6] This manner of generation is essential to achieve the coherence aspect of the new technique. With the variable rf attenuator disconnected, a normal pulse echo pattern is observed on the oscilloscope. By changing the VFO frequency the pulse echo pattern merely changes slightly in amplitude and decay rate. The maximum amplitude and minimum decay rate are simultaneously achieved by tuning the VFO frequency to coincide with the resonant frequency ν_T of the piezoelectric transducer. If a low level cw signal, obtained from the VFO via an rf attenuator, is

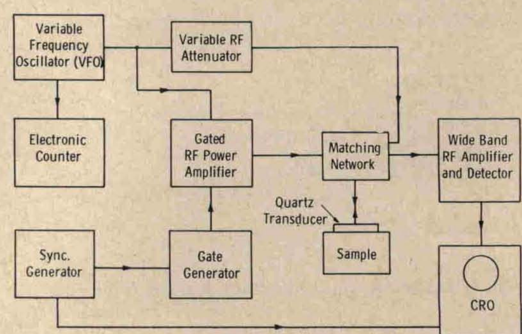

FIG. 4. Block diagram of pulse/cw system.