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THE METHOD OF MEASURING THE VELOCITY OF SURFACE ACOUSTIC WAVES BY LASER PROBING

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The method of measuring the surface acoustic wave velocity by probing it with a laser beam, whose width is greater than the acoustic wavelength, is proposed. The velocity is determined by measuring the time and space characteristics of the optical field of the beam reflected from the sample surface. The method is characterized by high accuracy and spatial resolution.

Keywords: *velocity of surface acoustic waves, laser methods.*

МЕТОД ВИМІРЮВАННЯ ШВИДКОСТІ ПОВЕРХНЕВИХ АКУСТИЧНИХ ХВИЛЬ З ДОПОМОГОЮ ЛАЗЕРНОГО ЗОНДУВАННЯ

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Запропоновано метод вимірювання швидкості поверхневої акустичної хвилі з допомогою зондування лазерним променем, ширина якого більша за довжину акустичної хвилі. Швидкість визначено шляхом вимірювання часових та просторових характеристик оптичного поля променя, відбитого від поверхні зразка. Метод характеризується високою точністю і просторовим розділенням.

Ключові слова: *швидкість поверхневих акустичних хвиль, лазерні методи.*

The velocity of the surface acoustic waves (SAW) is an effective tool for the investigation of the surface properties of solids, including medium with spatially inhomogeneous distribution of properties. This value depends on elastic characteristics and density and is sensitive to different processes occurring in the medium [1]. The investigation of the spatially inhomogeneous medium determines the spatial distribution of the SAW velocity. The accuracy and spatial resolution are the characteristics of such measurements [2].

Measuring of the SAW velocity includes measuring of the acoustic signal travel time and corresponding distance. The velocity measuring accuracy is determined by the accuracy of measuring of these values. The high spatial resolution can be gained by non-contact laser methods [3]. These methods are based on the interaction between the probing laser beam and the displacement of the sample surface caused by the acoustic wave. To determine the velocity of the SAW two cases are usually used. The first one is realized when the wavelength of the SAW is sufficiently small (tens of millimeter and less) and $D \gg \Lambda$ where D is the diameter of the laser beam in the region of interaction with SAW, Λ is the SAW wavelength. In this case the diffraction of the optical beam on the SAW is observed. The SAW wavelength and correspondingly its velocity can be measured by the diffraction angle measurement [4]. The SAW wavelength range usually exceeds the tens of MHz. The other case is realized when $D < \Lambda$. In this case the local displacement of the surface caused by the SAW is detected. The velocity is determined by measuring the time delay between the signals detected in different sample regions and the distance between them [5]. Such an approach is the most widespread and is used for methods with the optical detecting of the SAW and also for methods where the contact piezoelectric transducers are used.

The velocity measuring error in this case is represented by the expression [2]:

$$\left(\frac{\sigma_V}{V}\right)^2 = \frac{1}{(x_s)^2}(\sigma_x^2 + V^2\sigma_t^2) \ , \tag{1}$$

where σ_V, σ_x, σ_t are standard deviations in determination of velocity, distance and time, correspondingly; V is the SAW velocity; x_s is the distance at which the SAW velocity is determined. As can be seen from the above expression the increase in the distance x_s leads to the decrease in the velocity value measuring error. On the other hand, the increase in this distance causes the decrease in the spatial resolution, which is very important in the case of investigation of a spatially inhomogeneous object. Thus, the accuracy of the velocity measurement and spatial resolution are the inversely proportional values and these can not be improved simultaneously by selecting the distance x_s. We have proposed the method of measuring the SAW velocity which allows us to increase the accuracy of measuring without decreasing the spatial distribution. The method consists in probing the surface wave by a laser beam and can be classified as an intermediate case between the cases when $D >> \Lambda$ and $D < \Lambda$. In our case value of D is equal to several Λ. Similar geometry is considered as a method of SAW detection in [6].

In this case the spatial distribution of the probing optical beam intensity corresponds to the displacement of the sample surface caused by the SAW. Correspondingly, the SAW movement on the sample surface will cause the movement of the spatial distribution intensity of the optical field across the beam. In paper [6] a signal from the whole optical beam was detected simultaneously with the use of spatial amplitude modulator installed in front of a photodetector. Our method is based on detection of the signal in the small area of the optical beam. By locating the photodetector in different areas across the optical beam, the SAW can be detected in different areas of the sample.

The distance x_s on the surface of the sample changes into μx_s in the area of detection because of the probe beam expanding. The value μ is determined by expanding the probe beam. Expression (1) is written as:

$$\left(\frac{\sigma_V}{V}\right)^2 = \frac{1}{(\mu x_s)^2}(\sigma_x^2 + (\mu V)^2\sigma_t^2) \, . \tag{2}$$

The μ value for a specific geometry can be determined by calibration measurements using a sample with a known velocity V. Since a diverging beam is used, the value of $\mu x_s > x_s$, therefore the measurements are more accurate. According to expression (2) this will lead to the decrease in the error in measuring the SAW velocity. At the same time the spatial resolution is determined by the size of the probing laser beam spot on the tested sample surface and thus it does not change.

Numerical modeling of the optical field of the probing beam. To evaluate the opportunities of the proposed method numerical modeling of the intensity of the probing beam optical field was used. The spatial distribution of the probing beam intensity after reflection from the surface, on which the SAW is propagating, was determined. It is assumed that the SAW is propagating on the mirror surface. The Huygens–Fresnel principle was used to calculate the distribution of the intensity of laser beam reflected from the sample surface with the SAW. The 2D model was considered. Since the light velocity is much greater than the velocity of the SAW, the spatial distribution of the displacements on the sample surface was considered to be unchanged during the interaction of the optical beam and the SAW. The optical source amplitude distribution was assumed as Gaussian and is expressed as:

$$E(x_1) = \frac{1}{\sqrt{2\pi}} e^{-\frac{(x-x_0)^2}{2b^2}}, \tag{3}$$

where E is the optical field amplitude; x is the coordinate perpendicular to the direction of the optical beam propagation; b is the parameter of distribution.

The displacement of the sample surface caused by the SAW propagation is written as follows:

$$y = h\sin\left(\frac{2\pi}{\Lambda}x\right), \tag{4}$$

where h is the SAW amplitude; Λ is wavelength of the SAW.

Using the Huygens–Fresnel principle the optical field phase and amplitude were calculated by the following expression [7]:

$$E(x_i, y_j) = \frac{k}{2\pi i}\int_{-a}^{a} E(x_n, y_m)\frac{ze^{ikr}}{r^2}dx_j, \tag{5}$$

where $E(x_i, y_j)$ is the calculated amplitude of the optical field; $E(x_n, y_m)$ is the amplitude of the optical field on the source surface; k is the wave vector of the optical wave; z is the distance between the source surface and the area where the amplitude of the optical field is calculated; $2a$ is the size of the light source. Two successive steps were used in calculations. In the first step the optical field on the sample surface was calculated and in the second one – the optical field of the beam, reflected from the sample surface. The distribution of the optical field amplitude on the source surface corresponded to expression (3), and the phase was assumed to be constant. The spatial distribution of the optical field intensity was calculated from the distribution of the optical field amplitude by expression $I = E^2$.

The optical field intensity consists of the variable and constant parts. The variable part is related with the interaction of the optical beam and the SAW. Only the variable part of the intensity was detected experimentally, therefore in numerical modeling the value was used

$$\delta I = I_s - I_0, \tag{6}$$

where I_s is the optical field intensity with SAW; I_0 is intensity of the optical field without SAW.

Numerical modeling results. Numerical modeling allowed us to find the dependence of the $\delta I(x)$ value on the SAW wavelength. The obtained results are presented in Fig. 1. They show the spatial distribution $\delta I(x)$ for a laser beam reflected from the sample surface distorted by the SAW. The laser beam propagates in Y axis direction. The sample surface coordinate is $Y = 0$. The spatial distribution of $\delta I(x)$ is shown for a certain moment of time. When the SAW moves along the sample surface the spatial distribution of the optical field intensity will move too. It is seen that the spatial period of the optical field increases with the growth of the SAW wavelength. The spatial distribution of the intensity $\delta I(x)$ corresponds to the distribution of the sample surface displacement, caused by the SAW. This enables us to detect the SAW in different areas of the sample surface by a photodetector, located in different areas of the optical beam cross-section. Thus, by measuring the signal time shift and knowing the corresponding distance we can also determine the SAW velocity.

For the wavelengths Λ = 0.5 and 0.7 mm at some distance from the sample surface the violation of the periodicity is observed. At this distance there is a minimal change of the intensity across the optical beam.

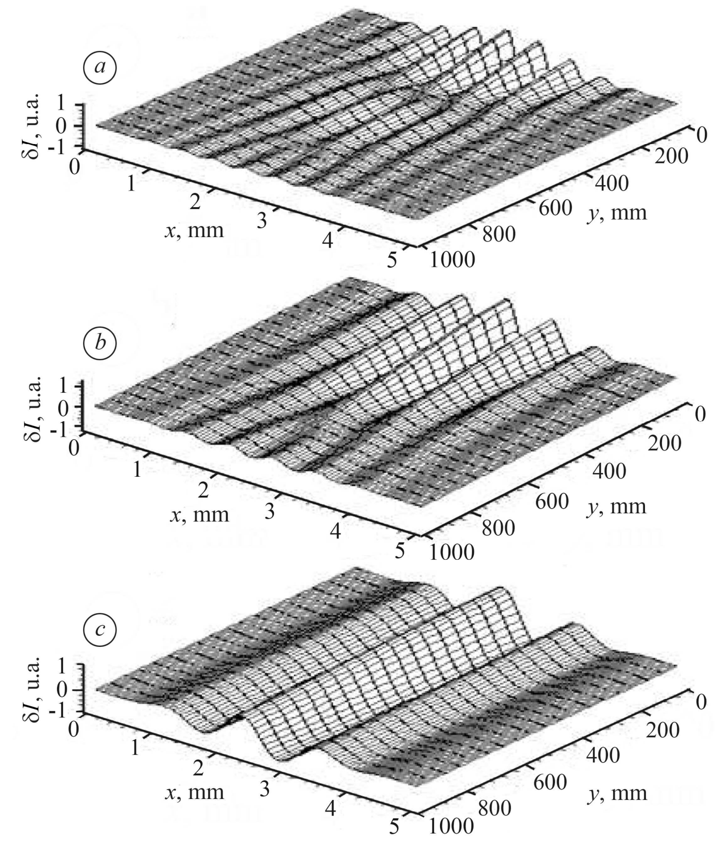

Fig. 1. The spatial distribution of the intensity change for laser beam reflected from the surface with SAW. The SAW wavelength is: *a* – Λ = 0.5 mm; *b* – Λ = 0.7 mm; *c* – Λ = 1.3 mm.

This violation of the periodicity is explained by the interference of the null order and two diffraction maxima of the ±1 order [5]. The first order diffraction maxima diffract at angles ±λ/Λ, where λ is the optical wavelength. Variation of the optical intensity is minimal when the phase displacement between the 0 and ±1 orders is $n\pi$, where $n = 1, 2\ldots$ This takes place at a distance from the sample surface [5]:

$$y = n\left(\frac{\Lambda^2}{\lambda}\right). \tag{7}$$

For the SAW wavelength 0.5 mm, 0.7 mm and 1.2 mm and λ = 0.63 μm and $n = 1$ this distance is 397 mm, 777 mm and 2286 mm, correspondingly. This agrees well with the numerical modeling results presented in Fig. 1.

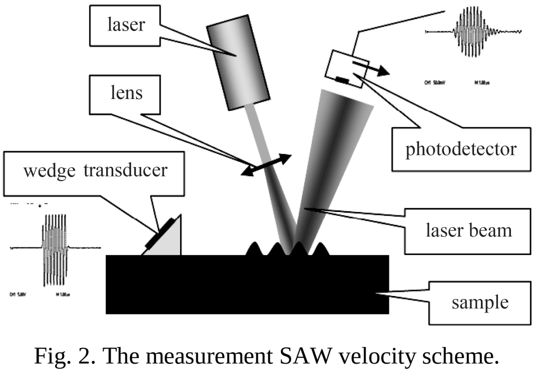

Fig. 2. The measurement SAW velocity scheme.

Experimental approbation of the method. The setup scheme for the measurement of the SAW velocity is shown in Fig. 2. The SAW was excited by the piezoelectric transducer on the wedge and propagates along the sample surface. The SAW velocity is measured by a laser probing beam. The probing laser beam is expanded by lens and reflected from the mirror surface of the sample. The

SAW displaces the sample surface. The spatial distribution of displacements on the sample surface changes spatial distribution of the reflected beam phase and produces periodical spatial intensity distribution, as shown in Fig. 1. The variable part of this intensity is detected by a photodetector.

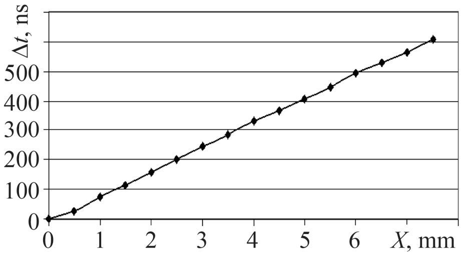

Fig. 3. The dependence of time shift of the signal on photodetector position across the laser beam.

The SAW was exited by modulation of sine signal with frequency 2.5 MHz and the width of input driving signal was 3 μs. Correspondingly the SAW wavelength was 1.25 mm. The He-Ne laser THORLABS HRR005 with wavelength equal to 0.6328 μm and power 0.5 mW was used. The optical signal was detected by photodiode S6468. The position of the photodetector was measured by the micrometer table. The signal was registered by oscilloscope TDS-1012. The digital signal from oscilloscope was recorded in the computer memory. The time shift of signals detected in different positions by the photodetector was determined by the correlation technique [8].

The dependence of the signal time shift on the photodetector position was measured. The results of experiment are shown in Fig. 3. The linear dependence of time shift on the photodetector position is obtained. The correlation coefficient between experimental and linear dependence is 0.9997, which corresponds to linear dependence between the time shift of the signal and the position of the photodetector. Consequently, it is possible to determine the value of μV from these data, which is 12100 m/s. As the velocity V is equal to 3100 m/s then $\mu = 3.9$ for this experiment geometry. Thus, the use of the sample with the known velocity allows us to calibrate the setup for the specific geometry of the experiment.

CONCLUSION

The laser method for measuring local velocity of a surface acoustic wave is proposed. The method is characterized by the high accuracy of the surface acoustic wave velocity measurements. By numerical modeling it is shown that intensity distribution across a probing optical beam corresponds to the displacement of the sample surface caused by the SAW. The linear dependence of the time shift of the signal on the position of the photodetector has been experimentally obtained, which allows us to measure the SAW velocity by the proposed method.

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