Laser optoacoustic non-destructive method of thickness measurement of subsurface damaged layer in machined silicon wafers

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Abstract. In the present work we propose the laser optoacoustic (OA) method for non-destructive measurement of the thickness of damaged layer in a machine cut silicon wafer. It is based on different mechanisms of laser excitation of ultrasound in monocrystalline silicon – the concentration-deformation mechanism and in a damaged layer – the thermoelastic one by absorption of Q-switched Nd:YAG laser pulse at the fundamental harmonic. Due to the uniform heating of a damaged layer during the laser pulse action the amplitude of the compression phase of the excited OA signal is proportional to the layer thickness. The rarefaction phase of OA signal arises by absorption of the rest of laser energy in monocrystalline silicon beneath the damaged layer. Comparison of the ratio of phase amplitudes with the scanning electron microscopy measurement of damaged layer thickness has shown it linear dependence vs. thickness within the variation of thickness and the corresponding spread of OA signal amplitudes. This provides the possibility of non-destructive laser optoacoustic measurement of the thickness of the damaged layer in silicon wafers. The minimum detectable value of the damaged layer thickness is of the order of 0.15-0.2 micron.

1. Introduction
Nondestructive measurements of the thickness of surface damaged layer in silicon wafers induced by machine cutting are critically important for its cost-effective manufacturing for microelectronic devices. Various methods are known for this measurement, such as, for example, X-ray diffraction, micro-Raman spectroscopy, ellipsometry, scanning electron microscopy and specific types of surface wave acoustic microscopy [1-4]. They provide accurate information on the thickness of the damaged layer but are very expensive and time consuming.

In the present work we propose the new laser optoacoustic method for non-destructive measurement of the thickness of surface damaged layer in a machine cut silicon wafer. Schematic image of the investigated wafer is shown in figure 1.

Figure 1. Investigated machine cut silicon wafer.
2. Brief theory of laser optoacoustic effect in silicon

The proposed method is based on different mechanisms of laser excitation of ultrasound in monocrystalline silicon and in a damaged surface layer by absorption of Q-switched Nd:YAG laser pulsed radiation (wavelength $\lambda=1.064 \, \mu m$, pulse energy $E=100 \, \mu J$, pulse duration $\tau_L=8\div10 \, ns$.) [5].

There is the concentration-deformation mechanism of ultrasound excitation by absorption of laser pulse in monocrystalline silicon, when the condition $\hbar \omega_L \geq E_g$ takes place ($\hbar \omega_L=1.17 \, \text{eV}$ is the light quantum energy, $E_g=1.12 \, \text{eV}$ is the band-gap energy for silicon). In this case all absorbed laser energy is spend to produce photoexcited electrons, so variation of density is determined by change of interaction forces between ions of crystalline lattice after electrons detachment from atoms and is not connected with heating of a crystal. Stress induced by generation of photoexcited electrons is:

$$p'_n = \rho_0 c_0^2 n/n_0 \, , \quad (1)$$

where $\rho_0$ and $n_0$ are an equilibrium density and a concentration of atoms, $n$ is the concentration of photoexcited electrons, $c_0$ is the acoustic wave velocity. Phenomenological description gives the expression:

$$p'_n = -d n \, , \quad (2)$$

where $d$ is the constant of deformation potential. For silicon $|d|=8 \, \text{eV}$, $d > 0$, so the photoexcitation causes the compression of a crystal.

In a damaged surface layer of a machine cut silicon wafer the crystalline structure is broken, so the life-time of photoexcited electrons substantially decreases due to their impact with structure defects and all laser energy absorbed in the damaged layer is thermalized during the laser pulse action. In this case the ultrasonic (optoacoustic - OA) signal consists of the thermoelastic part caused by heating and thermal expansion of the damaged layer and the adjacent immersion liquid - ethanol [6,7] (see below the experimental setup – figure 2) and the part caused by the concentration-deformation ultrasound excitation in monocrystalline silicon beneath the damaged layer.

3. Experimental setup

We used the experimental setup for optoacoustic investigations of silicon wafers with backward mode detection of acoustic signals [6,7]. A specially designed optoacoustic transducer was used (figure 2) providing laser irradiation of an investigated wafer through an optical fiber and wide-band piezoelectrical detection of acoustic signals from the same side of the wafer. An acoustical contact is provided by the immersion liquid (ethanol) transparent for the laser radiation. Electrical signals of the piezoreceiver are delivered to the digital oscilloscope, and then digitized signals are acquired and mathematically treated by PC with specially designed algorithms and computer codes.

![Figure 2](image-url)
No damage of investigated wafers takes place at the used level of laser radiation, so the proposed method is definitely non-destructive.

4. Experimental results and discussion
Temporal profiles of OA signals $S(t)$ in an etched monocrystalline wafer and in specimens of machine cut wafers are shown in figure 3. The instant of time $t = 0$ in figure 3 corresponds to the arrival of the laser pulse maximum on the front surface of the wafer. In the etched wafer the distribution of photoexcited electrons is uniform during the laser pulse action ($\mu_a H << 1$, $H$ is the wafer thickness, $\mu_a = 10$ cm$^{-1}$ is the interband light absorption coefficient). This corresponds to the negative plateau of OA signal following behind the negative front (compression of the silicon monocrystal). This front is determined by the convolution of the temporal profile of the laser pulse with the uniform distribution of photoexcited electrons, so the duration of this front is approximately of the laser pulse one. The positive plateau in this signal is the reflection of excited OA signal from the rear side of the wafer.

The OA signal in the machine cut wafer reveals first positive peak indicating the thermoelastic expansion of the heated surface damaged layer and the ethanol layer adjacent to it. We assume the uniform heating of the damaged layer during the laser pulse action because of the layer thickness is $L_d \approx 1\div2$ µm and the condition $\mu_a L_d << 1$ is satisfied. In this case the thermoelastic part of OA signal repeats the temporal profile of the laser pulse [6,7] and its maximum $A_+$ is observed at $t = 0$ (see figure 3). Only a small part of the laser radiation is absorbed in this layer, the most part penetrates it and is absorbed in monocrystalline silicon beneath the damaged layer. This corresponds to the rarefaction phase of OA signals (see figure 3), the negative plateau is not horizontal due to overlap of thermoelastic and concentration-deformation parts of OA signals. Due to the duration of the thermoelastic part is of the order of the laser pulse one, the amplitude of the concentration-deformation part $A_-$ is measured at the time instant $t > \tau_L$ ($t = 20$ ns). This instant corresponds to the OA signal excited at the depth $\approx 160$ µm in the wafer where are definitely no damages of crystalline structure.

The thermal expansion of the immersion liquid – ethanol – makes the main contribution to the thermoelastic part of OA signal [6, 7]. Since the heating temperature of the wafer damaged layer and ethanol respectively is the same for all wafers, the difference in amplitude values $A_+$ for different wafers is determined only by the efficiency of thermoelastic conversion in the damaged layer, that is directly proportional to the layer thickness (the volume of the thermooptical source of sound [5]).

Figure 3. Temporal profiles of laser-excited optoacoustic signals in silicon wafers.
There is no strong reflection of the positive peak of thermoelastic part of OA signal from the rear side of wafers (at the time instant $t \approx 30$ ns, see figure 3). This is due to its main part is determined by thermoelastic excitation of sound in the ethanol layer adjacent to the wafer and is practically fully reflected from silicon (the reflection coefficient $R_d = 0.9$). The only small part of this OA signal caused by the thermal expansion of the surface damaged layer passes into monocrystalline layer of the wafer and is reflected from its rear side. This leads to some increase of the positive plateau between 30 ns and 50 ns in comparison with the absolute amplitude $A_-$ of OA signal excited in undamaged crystalline silicon.

We compare the value $|A_+/A_-|$ with the scanning electron microscopy (SEM) measurements of $L_d$ for three silicon wafer specimens. An example of SEM image of machine cut wafer is shown in figure 4. Big grits at the chip are the pieces of wafer electrostalically attracted by the wafer break. We study the ratio of the amplitudes of compression and rarefaction phases of the OA signal to eliminate the influence of possible light reflection coefficient variation for different specimens. It was found that the dependence of $|A_+/A_-|$ vs $L_d$ can be fitted by a linear function. This dependence was used to get the reference curve, presented in figure 5, providing the possibility of the non-destructive laser optoacoustic measurement of the thickness of the surface damaged layer in silicon wafers from measured $A_+$ and $A_-$ values. The error bars in figure 5 are estimated from variations of OA signals amplitudes measured in different points of each wafer and from corresponding variations of $L_d$ determined by SEM. Evaluation of the minimum detectable thickness of damaged layer from the signal-to-noise ratio gives the value $L_{d_{\text{min}}} = 0.15 \pm 0.2 \, \mu m$.

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