Automatic Device for Measuring Minority Carrier Lifetime in Multicrystalline and Monocrystalline Silicon Using Noncontact Microwave Method.

Vladimirov V.M., Konnov V.G., Markov V.V., Repin N.S., Shepov V.N.

***Abstract*—**An automatic device for minority carrier lifetime measurements in multicrystalline and monocrystalline silicon by noncontact microwave method has been developed. To increase the accuracy of the minority carrier lifetime measurements a microwave module has been designed. To extend the resistivity range of the silicon samples measured a microwave sensor has been developed. The application results of this device for noncontact measurements of the minority carrier lifetime in monocrystalline and polycrystalline silicon is presented.

***Keywords*—**Microwave sensors; Elemental semiconductors; Microwave devices; Microwave measurements; Non-contact method.

I. Introduction

Non-contact microwave method for measuring minority carrier lifetime in silicon has long been known [1, 2]. The theory and physical principles of the method have been considered [3, 4, 5], and technology has been proposed [6-10], allowing one to measure minority carrier lifetime by non-contact microwave method.

With developing technologies for producing multicrystalline silicon with the addition of monocrystalline scrap, measuring devices based on non-contact microwave method became widely used. Such devices enable one to measure the minority carrier lifetime (MCL) in a wider range, including typical MCL both for monocrystalline and multicrystalline silicon.

However, to adjust the technology of producing multisilicon a non-contact microwave device is required allowing one to measure shorter minority carrier lifetime of the samples with lower resistivity. Developing such a device, meeting all the above mentioned conditions, requires the solution of several problems.

One of these problems consists in the necessity of automatic matching of the microwave oscillator frequency with the frequency of the microwave sensor, where the semiconductor measured is placed in the antinode of the microwave electric field. Matching should be made in a wide range of silicon resistivities, including typical resistivity values for the multicrystalline and monocrystalline silicon. To adjust the technology of the multisilicon production it is often necessary to measure MCL of the samples, with the resistivity ranging from 0.1 to 10 Ohm*cm, beginning from 100 nS. On the other hand, to control MCL of the monocrystalline silicon a measuring device is needed which is capable of measuring millisecond range MCL of the samples with the resistivity more than 1000 Ohm*cm.

In conventional measuring devices, as a rule, microwave oscillators were developed based on Gunn diodes. Microwave resonators were made based on waveguide transmission lines. The contact of the microwave resonator with the sample measured was made either through the hole in the waveguide wall [6-8], or through the inductive post in the below-cutoff waveguide [10]. Frequency matching was performed manually by trimming screw.

The application of self-excited oscillator schemes for measuring MCL by non-contact microwave method allows one to automatically control the frequency and minimal microwave power reflected from a semiconductor. However, in such schemes it is impossible to control the form of the resonance line, which is necessary when measuring MCL of the low-resistivity semiconducting samples. When measuring MCL of such samples the Q-factor of the fundamental oscillation mode of the microwave sensor used decreases considerably, resulting in the operation instability of the self-excited oscillator. Therefore, in order to measure MCL by non-contact microwave method in the wide resistivity range it is more

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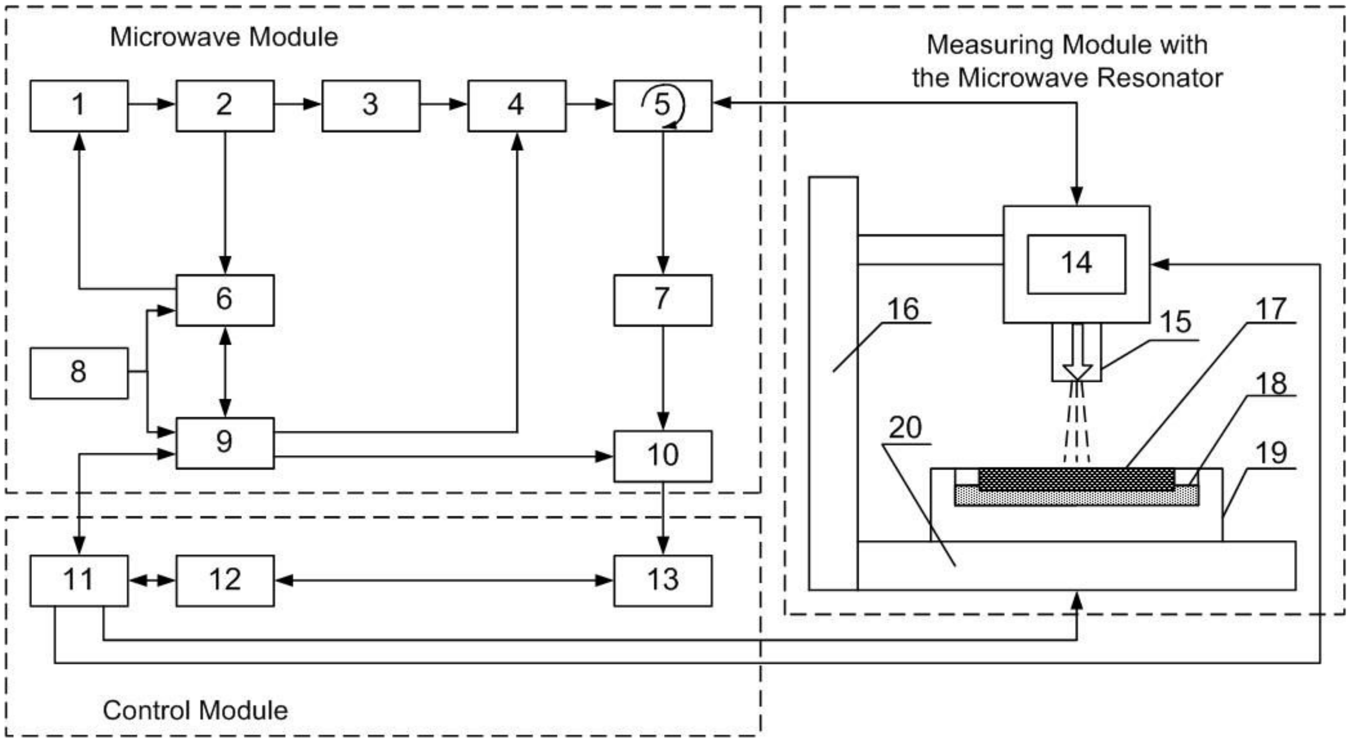

Fig. 1. The diagram of the measuring device «Taumeter-2M». 1- voltage-controlled oscillator; 2 – power divider; 3 – microwave amplifier; 4 – controlled attenuator; 5 – circulator; 6 – frequency synthesizer; 7 – power detector; 8 – reference oscillator; 9 – programmable logic integrated circuit; 10 – operation amplifier; 11 – control circuit board; 12 – computer; 13 – AD converter; 14- laser diode; 15 – microwave resonator, 16 – controlled mechanism of the microwave resonator movement, 17 – semiconductor measured, 18 – electrolytic bath, 19 – measuring table, 20 –control unit of the measuring table movement.

preferable to use the scheme of the controlled frequency sweep oscillator with visualization of the resonance curve [11-13]. In the present work such a microwave module has been developed allowing one to control not only the change of the frequency and amplitude of the microwave sensor resonance line but also the change of the resonance line form with further control of the Q-factor of the microwave sensor loaded with the semiconductor.

Another problem arising when developing the given measuring device is due to a larger difference both in the level of the microwave power reflected from low- and high-resistivity semiconductors and in the change of this level when the pulsed laser radiation acts upon the semiconductor. One of the possible solutions of this problem is to measure MCL of the high-resistivity samples using the method of transmitted microwave power (“transmission mode”), and MCL of the low-resistivity samples using the method of reflected microwave power (“reflection mode”). However, such a design of the measuring device is quite bulky. Moreover, using the “transmission mode” prevents from locating (placing) a semiconducting wafer into the electrolytic bath during the measurements. The bath is used for passivating the surfaces of the semiconductor and is necessary for decreasing the negative effect of the surface recombination.

To solve the problem of silicon MCL measurements in its wide resistivity range a microwave microstrip sensor has been developed which is highly sensitive to minimal changes of the microwave power reflected from the semiconductor [12-14].

The aim of the present work is to develop an automatic device for measuring minority carrier lifetime in multicrystalline and monocrystalline silicon by non-contact microwave method. The measurements are to be made in a uniform «reflection» mode. Such a configuration of the device allows one to carry out MCL measurements in the electrolytic bath for the passivation of samples. The device must have high positioning accuracy and make it possible to automatically measure lifetime maps.

II. MICROWAVE MODULE AND MICROWAVE MICROSTRIP SENSOR

The figure 1 shows the diagram of the device. The dashed line indicates the microwave module, control module and measuring module with the microwave resonator. The microwave module is designed based on digital phase-locked loop (PLL) of the voltage-controlled oscillator (VCO). The device functions in the following way. The control program command from personal computer (12) arrives at control circuit board (11) through USB port. The circuit board controller coordinates the operation of the programmable logic integrated circuit (PLIC) (9) and laser diode control circuit. PLIC controls the operation of the frequency synthesizer circuit (6), digital attenuator (4) and operation amplifier (10).

VCO (1) creates a microwave signal (Fc) in the frequency range from 4800 to 5300 MHz. The microwave signal is received by power divider (2) from VCO, with the part of this signal received by two-stage microwave amplifier (3), and the other part by digital frequency synthesizer (6). The signal with the frequency of 100 MHz (Fop) enters the other input of the synthesizer from the reference oscillator (8).

When comparing Fc/N and Fop/n, the frequency sweep amounts to 0.1 MHz. Frequencies are divided by built-in frequency dividers. Moreover, N – is a variable (controlled) division factor and n – is a constant one.

Created in the output of the phase-frequency detector (PFD) included in the frequency synthesizer is a control signal depending on the phase difference of the compared signals Fc/N and Fop/n. The voltage from the PFD output is fed to the input of the VCO control through dc-amplifier and low-pass filter and stabilizes the intended frequency.

Microwave power is transmitted from the amplifier output (3) to the controlled attenuator (4). The range of the attenuator tuning is 0 - 31.5 dB, with the step being 0.5 dB. Microwave power passing through the circulator (5) is transmitted from the attenuator, to the microwave microstrip sensor (15) loaded with the semiconductor sample being measured. To measure MCL in a wide range of the silicon resistivities the microwave power can be adjusted in the range of 0.01 -100 mW by digital attenuator.

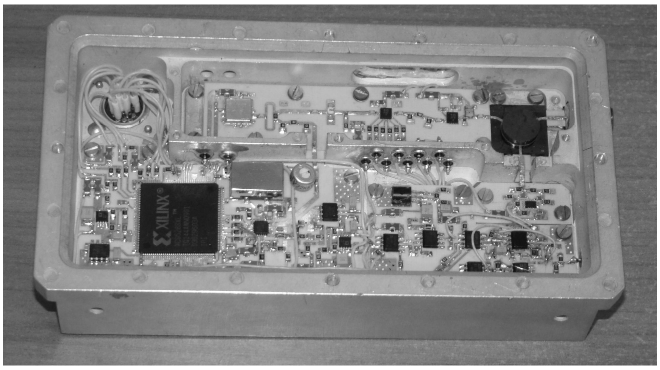

Fig. 2. Photograph of the microwave module.

The microwave signal reflected from the semiconductor enters the power detector (7) passing through the circulator (5). Then, the signal detected is enhanced by the operation amplifier with a controlled amplification factor (10). By means of the serial code received from PLIC the amplification factor can be varied from 1 to 20, resulting in the gain of the information signal up to the level necessary for the operation of a 12-bit analog-digital converter (ADC) (13). The maximal discretization frequency of ACD amounts to 100 MHz, the memory buffer capacity is 1024 kword. The ADC parameters allow one to measure the entire curve of the photoconductivity decay at one pulse of the laser radiation at the MCL values varying from 100 ns to 10ms.

The photo of the microwave module is given in Fig. 2.

The microwave sensor which couples the microwave oscillator and semiconductor sample measured is made based on the microstrip resonator (MSR) and operates in the «reflection mode». Fig. 3 shows the topology of the MSR strip conductor. MSR was fabricated on the substrate Rogers with permittivity of 3.44 and thickness of 0.5 mm. The width of the MSR strip conductor was 0.7 mm. A contact pad for the MSR capacitive coupling with the transmission line was cut out in the screen on the backside of the insulating substrate. The opposite ends of the strip conductor, with the antinodes of the high-frequency electric field being in the antiphase, are connected through the gap S [13,14]. The width of the conductor W1 may be the same along the whole length of MSR, as well as different from the W2 width at the conductor site of the length L2. This sharp change of the strip conductor width allows one to tuning the resonance frequency of the dominant mode used to measure the silicon MCL as well as adjusts the capacity value between the strip conductor end and grounded base.

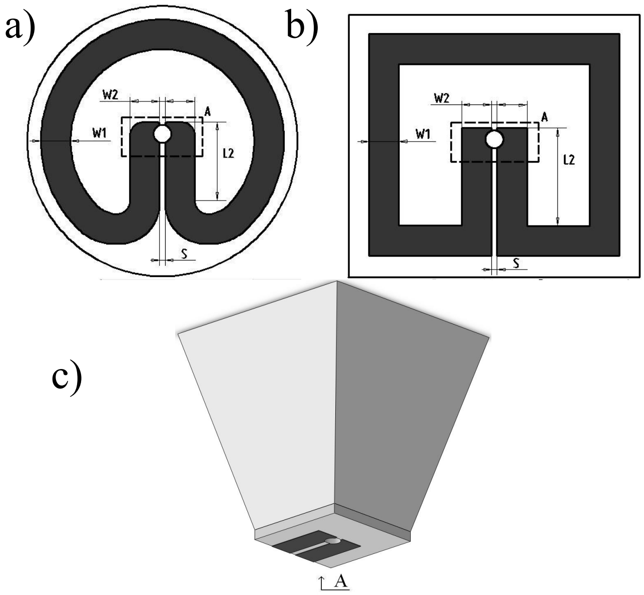

Fig. 3. Topology (a, b) and preferred embodiment (b) of the microstrip resonator.

There is a through-hole between the ends of the MSR strip conductor for the radiation of the laser diode mounted on the backside of the insulating substrate to pass. In the Fig. 3 (a, b) this part is outlined by a dashed line. The wavelength of the laser diode radiation is 1.06 μm and the maximum power of the continuous radiation is 500 mW.

As far as the design is concerned, this part of the device was implemented in such a way for the semiconductor measured to act only upon the area «A» indicated by the dashed line in Fig. 3 (a,b) rather than upon the whole MSR. The other part of MSR was located on the lateral side of the probe and connected with the area «A». One of the embodiments of such a microwave microstrip sensor design is given in Fig. 3 (c).

The sensitivity of such MSR is much higher than that of the resonator described in [11], resulting in the increased accuracy of measurements. This is due to the fact that in such MSR high-frequency electric field lines are shorted not only between the strip conductor and screen but also between the strip conductor antiphase ends acted upon by the semiconductor measured.

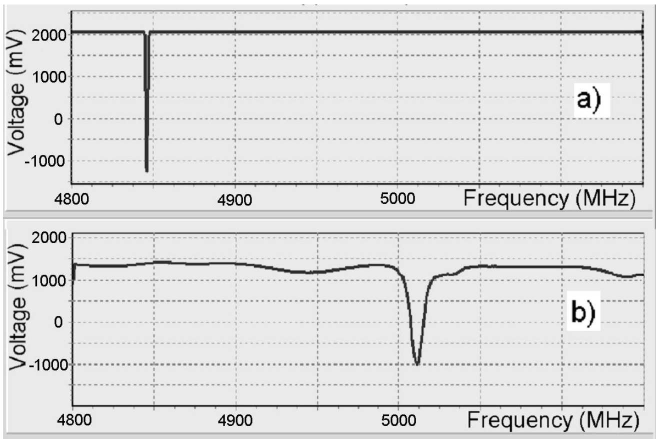

Fig. 4. The frequency dependencies of the microwave power reflected from the microwave microstrip sensor loaded with the silicon samples with the resistivity of 2500 Ohm*cm (a), and 0.05 Ohm*cm (b).

Fig. 4 shows frequency dependencies of the reflected microwave power from the microwave microstrip sensor loaded with the silicon samples, namely the curves (a) and (b), where F – is the signal frequency. These curves correspond to samples № 1 and № 2, which are monocrystalline and multicrystalline silicon samples of n-type, 6 mm and 3 mm in thickness, respectively. The resistivity value for sample № 1 is equal to 2500 Ohm*cm, and for sample № 2 – 0.05 Ohm*cm. One can see in the Figure that the developed microwave module with a specially designed microwave microstrip sensor enables one to reliably record the reflected microwave power in the silicon resistivity range from 0.05 to 2500 Ohm*cm. And this range is not ultimate.

For more detailed examination of the resonance line it is possible to arbitrarily change the frequency range of the microwave module (within the range 4800 – 5300 MHz). The frequency step is discrete, its minimum value being 0.1 MHz.

The measurements are controlled by a personal computer (12). For the automation of the MCL measurements the control program in the system Borland C ++ Builder has been created. With the help of the control program one can set the lower and upper boundary of the frequency tuning range of the microwave oscillator included into the microwave module, discretisation as well as duration and power of the laser diode radiation.

Fig. 5 shows the window of the control program. In the left part of the window one can choose adjustments of the microwave module and control module using the measuring table. The frequency dependence of the microwave power reflection coefficient is shown in the upper part of the window. In the lower part the time dependence of the photoconductivity of the sample measured is given. Then, a certain part of the curve is chosen manually or automatically for the treatment of the experimental data.

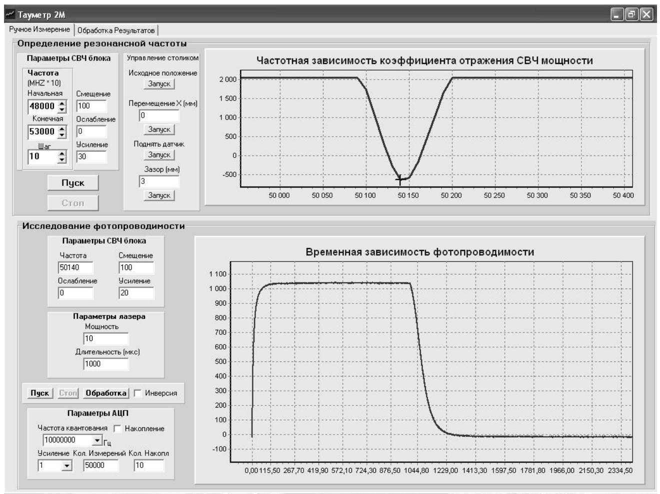

Fig. 5. The window of the control program.

The first controller of the control module coordinates the operation of the microwave module and control circuit which controls the radiation of the laser diode. The second controller controls over the vertical movement of the microwave resonator, linear movement and angular rotation of the measuring table (19), where the semiconductor being measured is placed. To measure the MCL map a detector of the angular movement of the measuring table is employed in the device. The accuracy of the repositioning is ~ 50 micron. The diameter of the effective laser beam spot is 2 mm. The diameter of the wafers of the semiconductor measured is up to 300 mm. In the device the second stabilized power supply is provided for feeding step motors, second microcontroller and circuits of the formation of the motor controlling impulses.

After establishing an optimal coupling between the microwave microstrip sensor and silicon sample measured a laser radiation pulse of the chosen duration and power upon the command of the control program passes through the hole in the MSR and excites the minority carriers in the semiconductor. The photoconductivity decay is recorded via the time dependence of the change of the resonance line amplitude or Q-factor of the microwave resonator.

The device operates in the following way. Using the command program one sets the upper and the lower limits of the frequency sweep of the microwave oscillator included into the microwave module as well as the sweep step. The power of the microwave oscillator is automatically regulated by the controlled attenuator and is fed to the microwave resonator through the microwave module circulator. The signal reflected from the semiconductor measured is detected and transmitted to the operation amplifier with the controlled amplification coefficient. The signal is transmitted from the amplifier to the A/D converter (13) and, then, to the computer.

III. Measurement results

Fig. 6 presents the measured time dependencies of the photoconductivity growth and decay for sample № 1 (the upper figure) and № 2 (the lower figure). The results for sample № 1 were obtained at the microwave module power of 2mW, with the power of the laser radiation unit pulse being 30 mW and its duration - 1000 μsec. And for sample № 2 they were obtained at the microwave module power of 80mW, with the power of the laser radiation unit pulse being 450mW and its duration - 50 μsec. 30 measurements were taken for sample 2. One can see in the figure that the microwave module with a specially designed microwave resonator enables one to reliably record the curves of the photoconductivity growth and decay using the technique of the reflected microwave power.

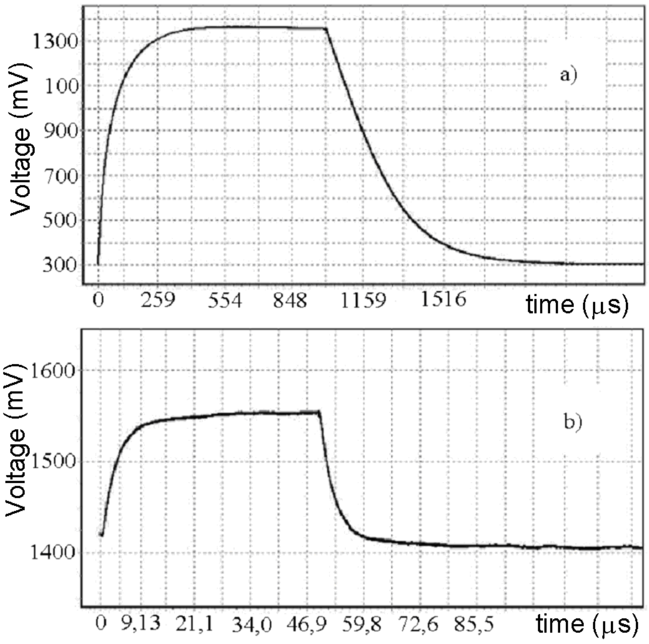

Fig. 6. The time dependences of the photoconductivity growth and decay for the sample with the resistivity of 2500 Ohm*cm (a) and 0.05 Ohm*cm (b)

From the obtained time dependencies of the photoconductivity the control program chooses automatically the section of the photoconductivity decay depending on the chosen standard of treating the experimental results. According to the international standard SEMI MF 1535 for measuring the effective MCL the lower part of the photoconductivity decay curve is chosen from 45 % to 5 % from the decay starting point. According to the standard SEMI MF 28b the upper part of the photoconductivity decay curve is chosen from the decay starting point to the point whose value is e times lower. Then, the experimental points on the curve section chosen are approximated by the exponential dependence. The control program also allows one to manually choose an arbitrary section of the photoconductivity decay for its further treatment.

The differences in the effective MCL when treating the results obtained using these two techniques are due to the entire photoconductivity curve not being described by a single exponent. In a general case, the relaxation curve is described by the semi-finite sum of the exponents [5]:

$$\Delta n(x,y,z,t)=\sum_{i,k} A_{ijk}\cos\left(\frac{\xi_i x}{a}\right)\cos\left(\frac{\eta_j y}{a}\right)* \\ *\cos\left(\frac{\zeta_k z}{a}\right)\exp\left(-t\left[\frac{1}{\tau_v}+v_{i,j,k}\right]\right) \qquad (1)$$

where $\Delta n(x,y,z,t)$ is the change of the minority carrier value, x, y, z are the spatial coordinates, t is the instant time, τ_v is the bulk MCL and a is the half of the sample thickness, A_{ijk} is the coefficient at (for) the ijk-th exponent (the contribution of the ijk-th exponent into the excessive concentration of the minority carriers), ξ_i, η_j, ς_k, are coefficients determined by the equations:

$$\frac{D}{Sa}\xi_i = ctg\xi_i, \quad \frac{D}{Sb}\eta_j = ctg\eta_j, \quad \frac{D}{Sc}\zeta_k = ctg\zeta_k, \qquad (2)$$

where α, b, c are the half-thickness, half-width and half-length of a sample, S is the rate of the surface recombination of the minority carriers, D is the minority carrier diffusion coefficient, ξ_{ijk} is the value determined by the following characteristic equation:

$$v_{ijk} = D\left(\frac{\xi_i^2}{a^2}+\frac{\eta_j^2}{b^2}+\frac{\zeta_k^2}{c^2}\right), \qquad (3)$$

The main difficulty is to determine the A_{ijk} coefficients in formula (1). This problem can be simplified by solving transcendental equations (2). These equations have the first solution in the range $0-\frac{\pi}{2}$, the second solution in the range $\pi-\frac{3}{2}\pi$ etc.; moreover, at $S \to 0$ one has $\xi=\eta=\varsigma=0$ and at $S \to \infty$, $\xi=\eta=\zeta=\frac{\pi}{2}$. Therefore, having chosen the experiment parameters from the condition v_{111} to be more than 90%, where it necessary to achieve thermodynamic equilibrium during the impulse of the laser radiation, and having made corresponding reductions the solution of equation (1) allows one to determine the photoconductivity decay using the formula:

$$U = c \cdot e^{\frac{t}{\tau_{eff}}} + const \;, \tag{4}$$

where τ_{eff} is the effective minority carrier lifetime, t is the time coordinate, U is the photoconductivity decay value, c is the calibration coefficient, *const* is the constant determined by the level of the reflected microwave power in the absence of the laser diode radiation. This constant depends on the semiconductor resistivity and is independent of the photoconductivity.

The bulk MCL is connected with the effective MCL by the following relation:

$$\frac{1}{\tau_V} = \left(\frac{1}{\tau_{eff}} - \frac{1}{\tau_s} \right), \tag{5}$$

where τ_v is the bulk MCL, τ_s is the time of the recombination. Here, the contribution of the recombination can be divided into two constituents: the diffusion and surface recombination:

$$\tau_S = \tau_{diff} + \tau_{sr} = \frac{d^2}{\pi^2 D} + \frac{d}{2S}, \tag{6}$$

where d is the sample thickness, π is the constant, S is the minority carrier surface recombination rate, D is the coefficient of the minority carrier diffusion. For the samples with the rough surface the surface recombination rate exceeds 10000 cm/s. When the sample thickness is more than 1 mm, the contribution of the second term in formula (6) is negligible. Thus, when processing experimental data the bulk lifetime is calculated by the formula:

$$\tau_v = \left(\frac{1}{\tau_{eff}} - \frac{\pi^2 D}{d^2} \right)^{-1}, \tag{7}$$

where the effective MCL is determined by formula (4). For thin wafers the sample passivation before taking measurements is necessary.

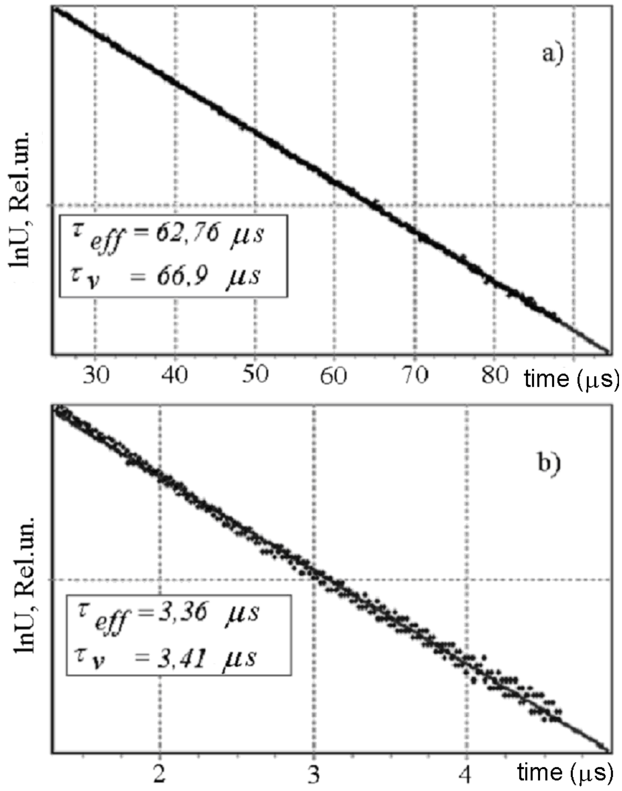

Fig. 7. The results of measuring the effective and calculating the bulk MCL

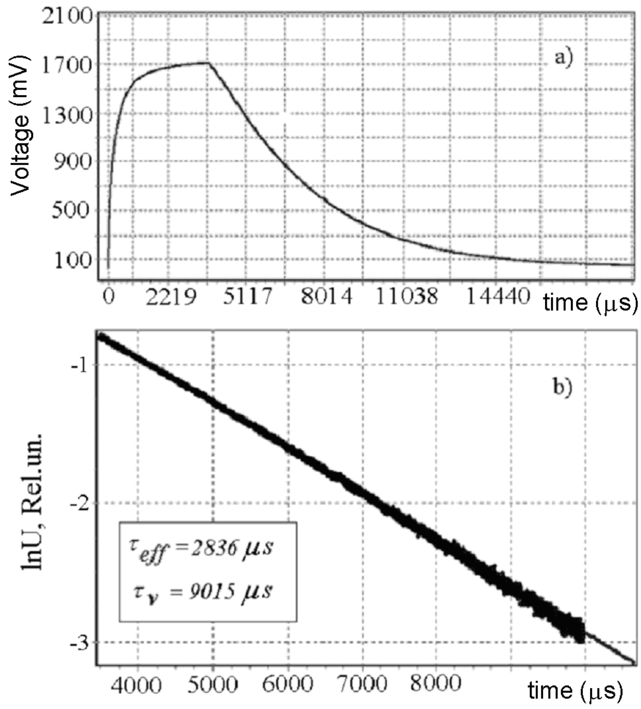

Fig. 8. The curve of the photoconductivity growth and decay (a) and calculation results of the effective and bulk MCL (b) for the monocrystalline silicon sample.

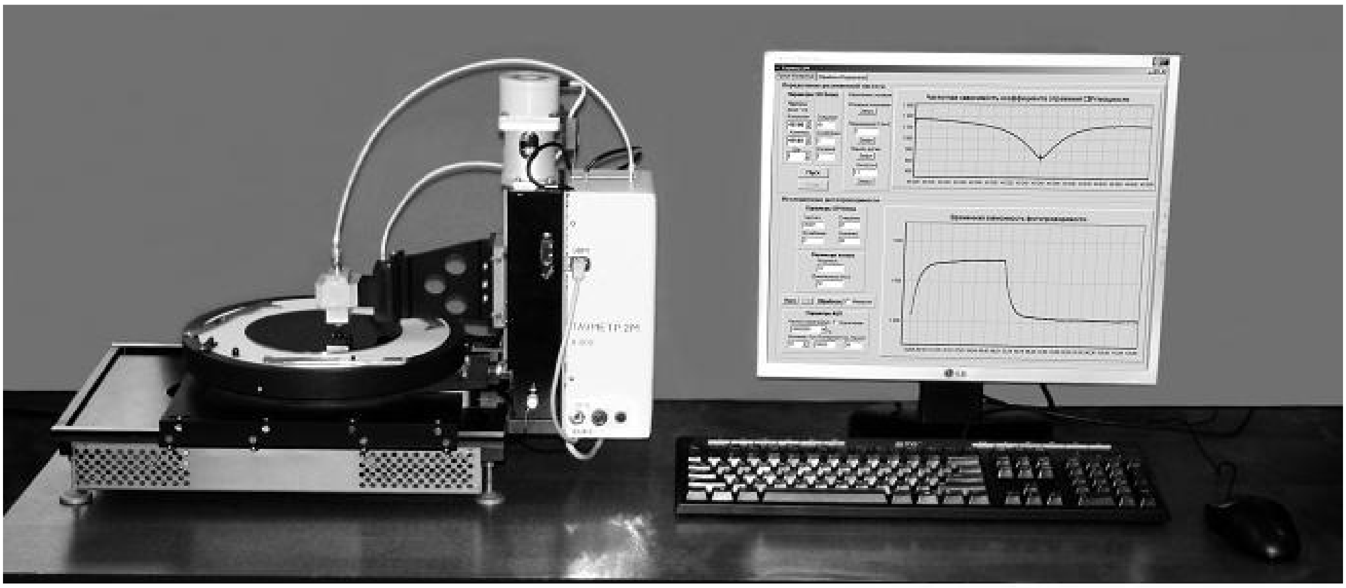

Fig. 9. The external view of the device «Taumeter-2M»

Fig. 7 presents the results of the effective MCL measurements and those of the bulk MCL calculation for samples № 1 and № 2 made according to the standard SEMI MF 28b, where *t* is the photoconductivity decay time, *ln U* is the photoconductivity amplitude logarithm. The difference between the effective and bulk MCL is quite small due to the large thickness of the samples (6 mm for the monocrystalline and 3 mm for the multicrystalline silicon).

Fig. 8 presents the measured time dependence of the photoconductivity growth and decay (a) and results (b) of the MCL measurements for the monocrystalline silicon of the p-type with the resistivity 1000 Ohm×cm. As one can see from the figure that the microwave module allows one to reliably record MCL of the millisecond range.

Fig. 9 shows the external view of the device developed.

IV. Conclusion

To sum up, in the given work a microwave module has been developed allowing one to control in automatic mode both the frequency and amplitude of the microwave sensor resonance line and the change of the resonance line form with further control of the Q-factor of the microwave sensor loaded with a semiconductor. The maximum frequency tuning range of the microwave module is equal to 4800 – 5300 MHz, and the minimum discretization is 0.1 MHz. The power adjustment ranges from 0.01 to 100 mW.

The developed microwave microstrip sensor is highly sensitive to minimal changes of the microwave power reflected from the semiconductor.

On the basis of the microwave module and microwave microstrip sensor a computer-aided device for microwave noncontact measurements of the minority carrier lifetime in silicon has been developed.

This device allows one to measure in automatic mode the minority carrier lifetime in multicrystalline and monocrystalline silicon in the range of 0.1 – 10000 μS. The resistivity range of the silicon samples is equal to 0.01 – 10000 Ohm*cm. The control of the resonance line form allows one to control possible distortions of the resonance line while taking measurements, thus increasing the accuracy of the MCL measurements.

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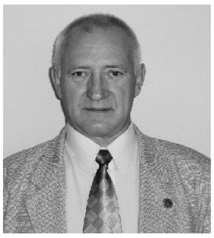

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