Semiconductor Minority Carrier Lifetime Meter Using Noncontact Microwave Method "TAUMETER – 2M".

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Abstract – A computer-aided device for microwave noncontact measurements of silicon parameters has been developed. The 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 0.01 – 10000 Ohm*cm. The results of applying this device for noncontact measurements of the minority carrier lifetime in silicon are presented.

Key-Words – Elemental semiconductors; Microwave devices; Microwave measurements.

1 Introduction

The 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], and technology has been proposed [5-9], 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 [5-8], or through the inductive post in the below-cutoff waveguide [9]. 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 preferable to use the scheme of the controlled frequency sweep oscillator with visualization of the resonance curve [10, 11]. 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. To solve this problem a microwave microstrip sensor highly sensitive to minimal changes in the reflected microwave power has been developed [12].

The aim of the work is to develop microwave module and microwave microstrip sensor for the device measuring silicon MCL by non-contact microwave method. Measurements should be made in a uniform mode, namely «reflection mode».

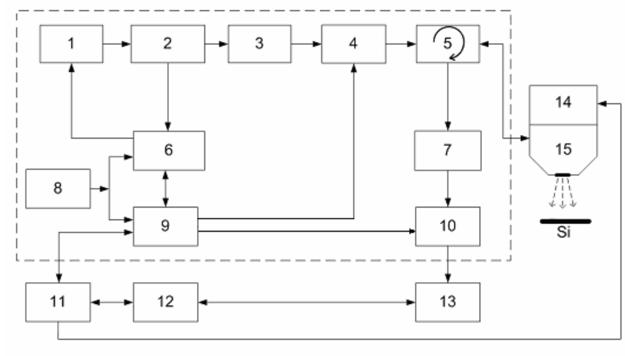

Fig. 1 Diagram of the measuring device "TAUMETER-2M". 1 – voltage-controlled oscillator; 2 – power divider; 3 – microwave amplifier; 4 – controlled attenuator; 5 – circulator; 6 – frequency synthesizer; 7 – power detector; 8 – reference oscillator; 9 – programmable logic integrated circuit; 10 – operation amplifier; 11 – control circuit board; 12 – computer; 13 – AD converter; 14 – laser diode; 15 – microwave resonator.

2 Microwave module and microwave microstrip sensor

Fig. 1 presents the diagram of the device, with the dashed line indicating the structure of the microwave module, designed on the basis of the digital 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), and, further, through the circulator (5) to the microwave microstrip sensor (15) loaded with the semiconductor sample 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.

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 down to 100 ns.

The microwave sensor which couples the microwave oscillator and semiconductor sample

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measured is made based on the microstrip resonator (MSR) and operates in the «reflection mode». Fig. 2 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 [12]. 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 L. 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.

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. 2 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.

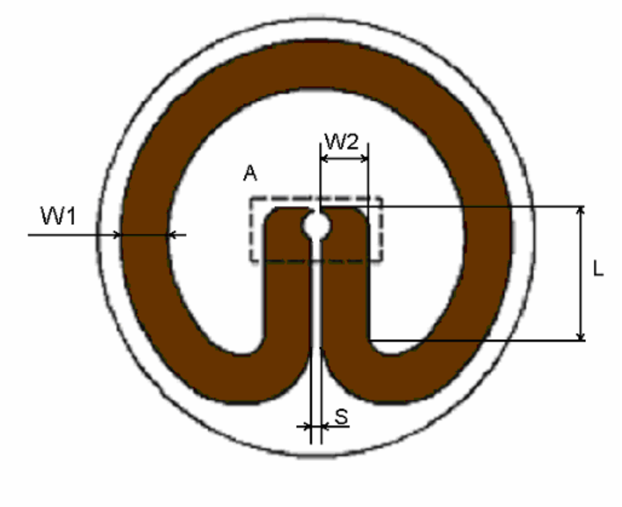

Fig. 2. Topology of the microstrip resonator.

In the preferred embodiment 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. 2 rather than the whole MSR. The other part of MSR was located on the lateral surface of the probe and connected with the area «A».

The sensitivity of such MSR is much higher than that of the resonator described in [10], 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. 3. Frequency dependencies of the microwave power reflected from the microwave microstrip sensor, loaded with the silicon samples with the resistivity of (a) – 2500 Ohm*cm, and (b) – 0.06 Ohm*cm.

Fig. 3 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 – 0.06 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 0.06 to 2500 Ohm*cm. And this range is not ultimate.

It is possible to arbitrarily change the frequency range within the range 4800 – 5300 MHz in order to examine the resonance line in more details. The frequency step is discrete, its minimum value being 0.1 MHz.

3 Measurement results

After establishing an optimal coupling between the microwave microstrip sensor and silicon sample measured a laser radiation pulse of the chosen

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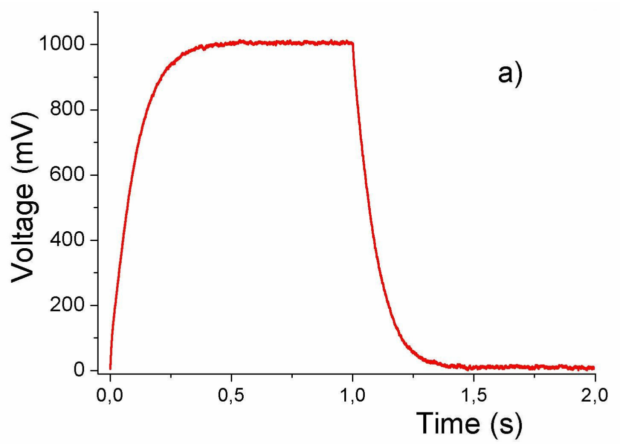
duration and power upon the command of the control program passes through the MSR through-hole and excites the minority carriers in the semiconductor. The photoconductivity decay is recorded via the time dependence of the change of the resonance line amplitude or Q-factor of the microwave resonator. Further, the effective MCL is estimated by the decay section of the photoconductivity curve and the bulk MCL is calculated according to the international standards SEMI MF 1535 and SEMI MF 28b.

Fig. 4 presents the measured time dependencies of the photoconductivity growth and decay for sample № 1 (the upper figure) and № 2 (the lower figure).



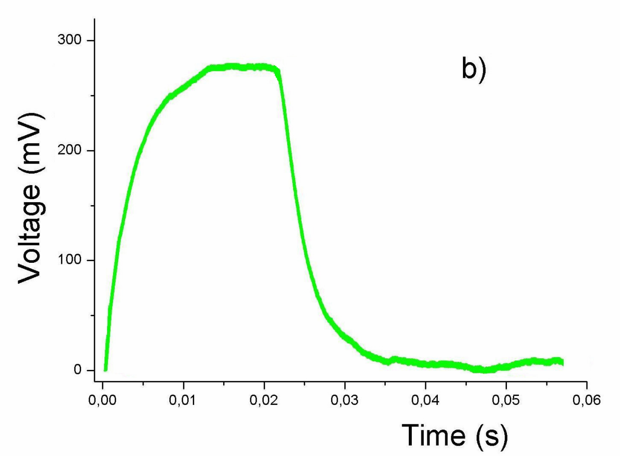


Fig. 4. Time dependences of the photoconductivity growth and decoy for samples with the resistivity of 2500 Ohm (a) and 0.06 Ohm (b).

The results for sample № 1 were obtained at the microwave power of 2mW, with the power of the laser radiation unit pulse being 30 mW and its duration - 1000 μS. And for sample № 2 they were obtained at the power microwave of 80mW, with the power of the laser radiation unit pulse being 450mW and its duration - 50 μS. 30 measurements were taken.

As can be seen in the figure, the device, based on the developed microwave module with a specially designed microwave microstrip sensor enables one to reliably record the curves of the photoconductivity growth and decay using the technique of the reflected microwave power.

Fig.5 presents the external view of the device developed.

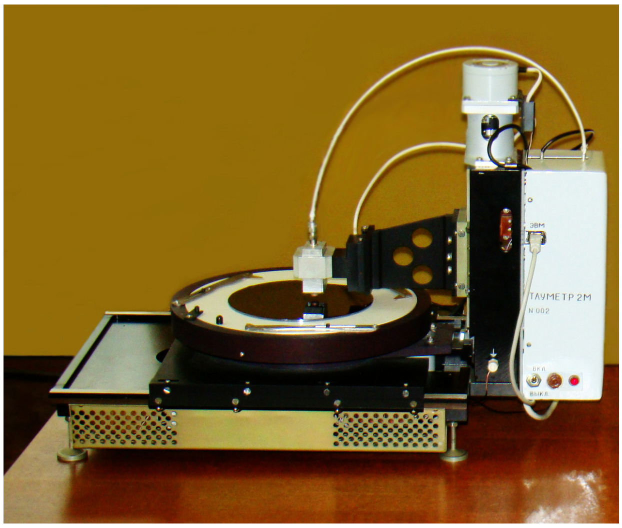


Fig. 5. External view of the device «Taumeter-2M»

4 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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