Inductive Type Impedance of Mo/*n*-Si Barrier Structures Irradiated with Alpha Particles

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In silicon microelectronics, flat metal spirals are formed to create an integrated inductance. However, the maximum specific inductance of such spirals at low frequencies is limited to a value of the order of tens of microhenries per square centimeter. Gyrators, devices based on operational amplifiers with approximately the same specific inductance as spirals, are also used. Despite the fact that such solutions have been introduced into the production of integrated circuits, the task of searching for new elements with high values of specific inductance is relevant. An alternative to coils and gyrators can be the effect of negative differential capacitance (i.e., inductive type impedance), which is observed in barrier structures based on silicon.

The purpose of the work is to study the low-frequency impedance of Schottky diodes (Mo/*n*-Si) containing defects induced by α-particles irradiation and determination of the parameters of these defects by methods of low-frequency impedance spectroscopy and DLTS (Deep Level Transient Spectroscopy).

Unpackaged Schottky diodes Mo/*n*-Si (epitaxial layer of 5.5 μm thickness and resistivity of 1 Ohm·cm) produced by JSC "Integral" are studied. Inductance measurements were carried out on the as manufactured diodes and on the diodes irradiated with alpha particles (the maximum kinetic energy of an α-particle is 5.147 MeV). The impedance of inductive type of the Schottky diodes at the corresponding DC forward current of 10 μA were measured in the AC frequency range from 20 Hz to 2 MHz. DLTS spectra were used to determine the parameters of radiation-induced defects. It is shown that irradiation of diodes with alpha particles produces three types of radiation-induced defects: *A*-centers with thermal activation energy of $E_1 \approx 190$ meV, divacancies with activation energies of $E_2 \approx 230$ meV and $E_3 \approx 410$ meV, and *E*-centers with activation energy of $E_4 \approx 440$ meV measured relative to the bottom of *c*-band of silicon.

Keywords: Schottky diode on silicon, negative differential capacitance, alpha irradiation, *A*-centers, *E*-centers, divacancies.

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Импеданс индуктивного типа барьерных структур Mo/*n*-Si, облученных альфа-частицами

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В кремниевой микроэлектронике для создания интегральной индуктивности формируют плоские металлические спирали. Однако максимальная удельная индуктивность таких спиралей на низких частотах ограничена значением порядка десятков микрогенри на квадратный сантиметр. Используются также гираторы – устройства на основе операционных усилителей, примерно с такой же удельной индуктивностью, как и спирали. Несмотря на то, что такие решения внедрены в производство интегральных микросхем, актуальной является задача поиска новых элементов с большими значениями удельной индуктивности. Альтернативой спиралям и гираторам может стать эффект отрицательной дифференциальной емкости (т. е. импеданса индуктивного типа), наблюдаемый в барьерных структурах на кремнии.

Цель работы – исследование низкочастотного импеданса диодов Шоттки (Mo/*n*-Si), содержащих радиационные дефекты, создаваемые α-частицами, и определение параметров этих дефектов методами низкочастотной импедансной спектроскопии и спектроскопии DLTS (Deep Level Transient Spectroscopy).

Исследованы бескорпусные диоды Шоттки 5.5КЭФ-1 (Mo/*n*-Si) производства ОАО «Интеграл». Измерения индуктивности проводились на исходных диодах и на диодах, облученных альфа-частицами (максимальная кинетическая энергия α-частицы 5.147 МэВ). В интервале частот переменного тока от 20 Гц до 2 МГц измерен импеданс индуктивного типа диодов при постоянном прямом токе 10 мкА. Для определения параметров радиационных дефектов измерялись спектры DLTS. Показано, что при облучении диодов Шоттки альфа-частицами образуется три типа радиационных дефектов: *A*-центры с энергией термической активации $E_1 \approx 190$ мэВ, дивакансии с энергиями активации $E_2 \approx 230$ мэВ и $E_3 \approx 410$ мэВ и *E*-центры с энергией активации $E_4 \approx 440$ мэВ, отсчитанные от дна *c*-зоны кремния.

Ключевые слова: диод Шоттки на кремнии, отрицательная дифференциальная емкость, альфа-облучение, *A*-центры, *E*-центры, дивакансии.

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Introduction

In silicon microelectronics, flat film spirals of round or rectangular shape are formed to create an integrated inductance. However, the maximum specific inductance of such spirals at low frequencies is limited to a value of the order of tens of microhenries per square centimeter, while their diameter can be of several millimeters [1]. Another way to create an integrated inductance is gyrators – devices based on operational amplifiers that imitate inductance [2, 3]. Despite the fact that such solutions have been introduced into the production of integrated circuits, the task of searching for new elements with inductive impedance is relevant. This will allow more rational use of the useful area of the microcircuits.

An alternative to film coils can be the effect of negative differential capacitance [4, 5], which is observed in various semiconductor structures: silicon photodiodes irradiated with neutrons, multilayer heterostructures, chalcogenide films, transistor structures, metal–semiconductor interfaces, etc. [6]. Note that, in metal–semiconductor barrier structures, hopping conduction via defects is observed in the forward biased space charge region of semiconductor [7].

The purpose of the work is to study the low-frequency impedance of Schottky diodes (Mo/*n*-Si) with radiation-induced defects for different fluences of α-particles and determination of the parameters of radiation-induced defects by DLTS spectroscopy.

Studied structures

Unpackaged Schottky diodes Mo/*n*-Si (epitaxial 5.5 μm thick layer and resistivity of 1 Ohm·cm) produced by JSC "Integral" were studied [8]. Diodes were fabricated on wafers of monocrystalline silicon of *n*-type electrical conductivity doped with antimony and grown by the Czochralski method. The resistivity of the wafers was 0.01 Ohm·cm at the laboratory conditions. The thickness of the wafers was 460 μm. An *n*-type 5.5 μm thick silicon layer was epitaxially grown on the substrate. Then, 0.3 μm thick molybdenum (Mo) layer was deposited in a vacuum (see Figure 1*a* and Table). The ohmic contact was formed by deposition of aluminum (Al) 3.3 μm thick layer on molybdenum. On the reverse side, an ohmic contact was formed by deposition of Ti/Ni/Ag (0.1/0.5/0.6 μm) metal electrode. Then the wafer was cut into chips (unpackaged barrier structures). After measuring the

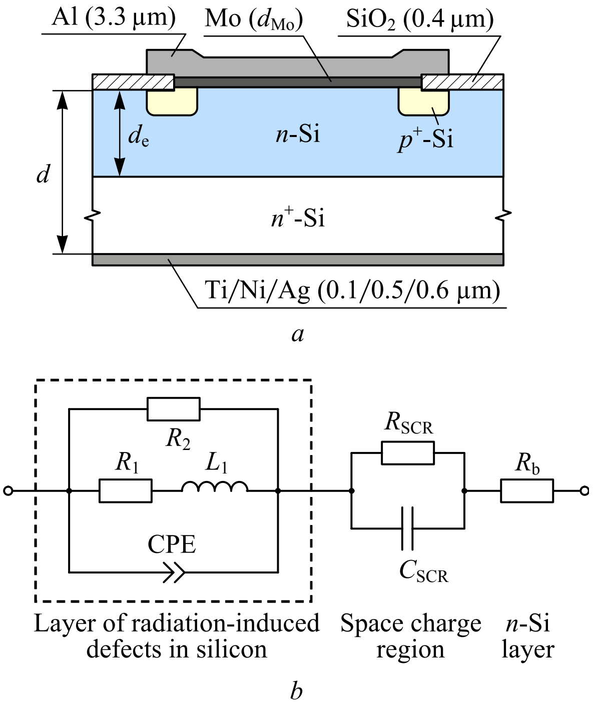

Figure 1 – Cross section of a Schottky diode (*a*) and equivalent electrical circuit (*b*) of an irradiated diode under forward bias U_{dc} = 50–100 mV (I_{dc} = 10 μA)

initial characteristics, the diodes were irradiated with an uncollimated beam of alpha particles (decay energy of 5.147 MeV) with fluence from $3.6 \cdot 10^{11}$ to $2.1 \cdot 10^{14}$ cm^{-2}. The projective range of α-particles in silicon did not exceed 24 μm. The surface activity of the source was $2 \cdot 10^{7}$ Bq·cm^{-2}. The diode equivalent circuit describing $Z(f)$ dependences at I_{dc} = = 10 μA is shown in Figure 1*b* (see also [9]).

Measurement results and their discussion

The dependences of the real Z' and imaginary Z'' parts of the impedance $Z = Z' + iZ''$ on the AC frequency f (in the range from 20 Hz to 2 MHz) and

Table

The main characteristics of the studied Mo/*n*-Si Schottky diodes at the laboratory conditions

Parameter	Value
Electrical resistivity of the *n*-type silicon epitaxial layer doped with phosphorus, Ohm·cm	1
Epitaxial layer thickness d_e, μm	5.5
Molybdenum layer thickness d_{Mo}, μm	0.3
Diode thickness d, μm	460
Barrier (transition) area, mm^2	5.25
Barrier capacitance C_b, nF	0.95 1.25 1.48

DC bias voltage U_{dc} (in the range from 0 to 400 mV) were measured on an Agilent E4980A LCR meter. AC signal amplitude was U_{ac} = 40 mV. When measuring the impedance *Z*, the diodes were kept in the dark at room temperature. DC forward current I_{dc} through the diodes varied from 0 to 10 mA; the characteristics were chosen at I_{dc} = 10 µA with the highest value of the "inductive type" impedance. The calculation of the diode inductance *L* was carried out according to the methods [9–11] using a series equivalent *LR*-circuit (see, e.g., [12]).

Figure 2*a*,*b*,*c* shows the frequency dependences of the inductance for diodes with the concentration of doping impurity (phosphorus) in the epitaxial layer: $3\cdot10^{15}$, $4.7\cdot10^{15}$, $7\cdot10^{15}$ cm^{-3}, corresponding to the values of the barrier capacitance: C_b = 0.95, 1.25, 1.48 nF. The barrier capacitance of the diodes and the concentration of phosphorus in the *n*-Si epitaxial layers were determined from measurements of the capacitance–voltage characteristics at the frequency of 1 MHz under the diode reverse bias of up to 10 V. For the first group of doping (Figure 2*a*), after irradiation, a significant increase in low-frequency inductance is observed, which then decreases with the fluence of α-particles. For all groups of diodes (Figure 2*a*,*b*,*c*) for fluences $\Phi = 1.7\cdot10^{13}$ and $3.5\cdot10^{13}$ cm^{-2} there is a decrease in the low-frequency inductance with the transition of the impedance to the capacitive type. When the fluence $\Phi = 5.2\cdot10^{13}$ cm^{-2} was reached, all three groups acquired an inductive impedance in the low-frequency region.

The maximum low-frequency inductance in both the virgin and irradiated Schottky diodes was found for the value of stationary current $I_{dc} \approx 10$ µA excited in them. According to Figure 2*a*,*b*,*c* the dependence of the inductance *L* on the frequency *f* of the measuring signal for $I_{dc} \approx 10$ µA has two extremes: the first (indicated by the Roman numeral *I* and marked by a dashed line) in the low-frequency region (75 Hz), the second (indicated by the Roman number *II* and marked with a dashed line) in the region (1–10 kHz) with capacitive impedance. (The negative inductance of a two-terminal network corresponds to the capacitance.)

So: i) the inductive contribution to the impedance of the diodes (*I* region) non-monotonically depends on the fluence of α-particles and decreases with the concentration of doping impurity (phosphorus); ii) the capacitive contribution to the impedance of the diodes (*II* region) increases with the

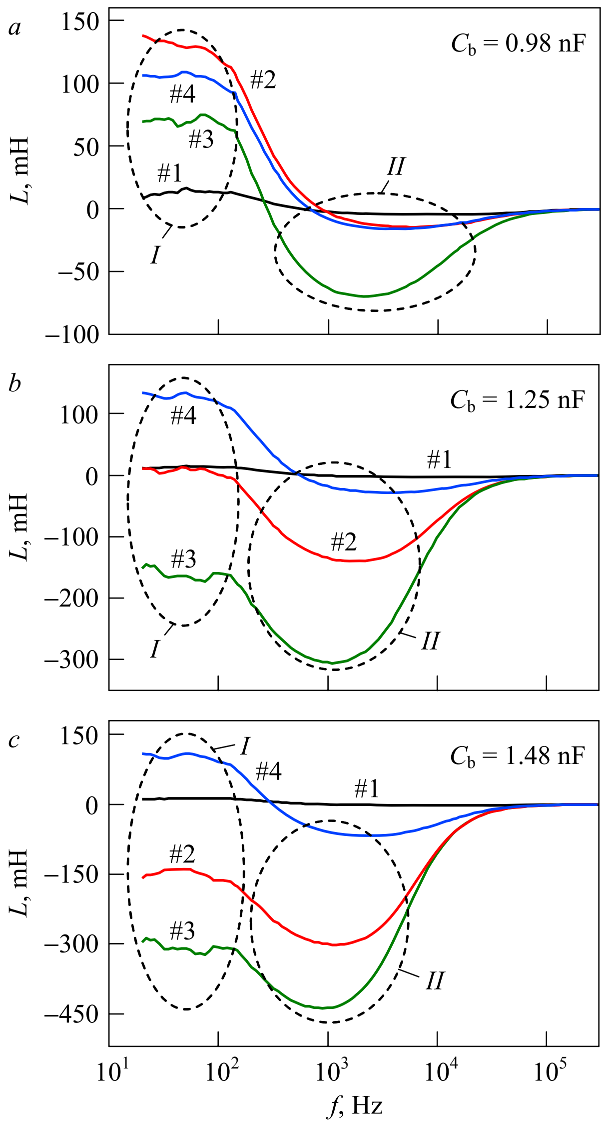

Figure 2 – Frequency dependences of the inductance *L* of three diodes with different barrier capacitance C_b. Numbers of curves correspond to fluences of α-particles Φ, 10^{13} cm^{-2}: 0 (#1); 1.7 (#2); 3.5 (#3); 5.2 (#4). The concentration of phosphorus atoms in the epitaxial silicon layer, 10^{15} cm^{-3}: 3 (*a*); 4.7 (*b*); 7 (*c*). Values of $L < 0$ correspond to the capacitive type of impedance

irradiation fluence and the concentration of phosphorus atoms.

Radiation-induced defects in diodes irradiated with α-particles were studied by DLTS spectroscopy [13–16] on CE-7C capacitance spectrometer in the temperature range from 80 to 300 K. DLTS spectra were recorded for diode irradiated with fluence of α-particles $\Phi \approx 3.6\cdot10^{11}$ cm^{-2}. The spectra were measured at the following setup parameters: filling pulse amplitude +5 V and duration 10 ms, reverse bias voltage –6 V, emission velocity window 19 s^{-1}.

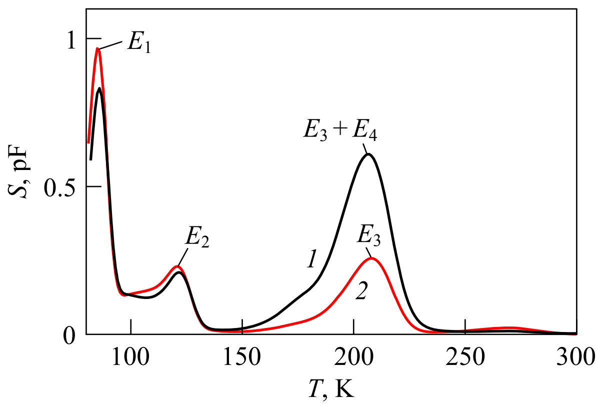

Figure 3 – DLTS spectra of the diode irradiated with α-particles with fluence $\Phi \approx 3.6 \cdot 10^{11}$ cm^{-2} ($C_b = 1.48$ nF; see also Table and Figure 2*c*): after irradiation (spectrum *1*); after annealing at 150 °C for 30 min (spectrum *2*)

Figure 3 shows DLTS spectrum of diode irradiated with α-particles with fluence $\Phi \approx 3.6 \cdot 10^{11}$ cm^{-2} (spectrum *1*) and DLTS spectrum of the same diode after 30 min annealing at the temperature of 150 °C (spectrum *2*).

Spectrum *1* shows DLTS peaks labeled E_1, E_2, E_3, and E_4. Each peak is associated with the emission of electrons from deep levels of radiation-induced defects. For each peak, from the Arrhenius dependences for deep levels, the values of the activation energy and the electron capture cross section were obtained. Peak E_1 corresponds to electron emission from the level $E_c - 0.19$ eV and capture cross section $\sigma_n = 1.4 \cdot 10^{-15}$ cm^{-2}, peak E_2 corresponds to $E_c - 0.23$ eV and $\sigma_n = 1.4 \cdot 10^{-15}$ cm^{-2}. The overlap of peaks E_3 and E_4 in spectrum *1* does not allow one to correctly determine the parameters of the corresponding defect levels.

Comparison of the obtained results with the literature data [13, 15] allows us to conclude that the E_1 peak corresponds to the deep level of the *A*-center, which is an "interstitial oxygen – vacancy" pair $(O\text{–}V)^{-/0}$. The E_2 peak belongs to the shallow divacancy level $(V\text{–}V)^{=/-}$. The E_3 peak is most likely associated with the emission of electrons from the deep divacancy level $(V\text{–}V)^{-/0}$ and corresponds to $E_c - 0.41$ eV and $\sigma_n = 1.7 \cdot 10^{-15}$ cm^{-2} [13, 15, 16].

The concentration of phosphorus doping impurity in the *n*-region of the studied Schottky diode is $4.7 \cdot 10^{15}$ cm^{-3}. At such dopant concentrations, along with the interstitial oxygen atoms, the phosphorus atoms also provide sinks for vacancies generated by alpha particles during irradiation [13, 17]. Therefore, the E_4 peak most likely corresponds to the electron emission from the deep level $E_c - 0.44$ eV and $\sigma_n = 1.7 \cdot 10^{-15}$ cm^{-2} of the phosphorus–vacancy defect $(P\text{–}V)^{-/0}$, i.e. *E*-center. To test this assumption, the irradiated diode was annealed, since it is known that annealing temperature of the *E*-center in about 150 °C [17]. Spectrum *2* in Figure 3 was recorded after annealing the irradiated sample at temperature of 150 °C for 30 min. It can be seen from this spectrum that the E_4 peak disappears after the heat treatment and only the E_3 peak remains.

Conclusion

It has been established that in the studied range of fluences of irradiation with α-particles (up to $\Phi = 5.2 \cdot 10^{13}$ cm^{-2}) Schottky diodes have a non-monotonic dependence of the inductance L on the fluence of α-particles. A significant increase in the inductance L for $f \approx 75$ Hz is observed (e.g., by an order of magnitude at fluence $\Phi \approx 5.2 \cdot 10^{13}$ cm^{-2} of α-particles). All irradiated diodes have capacitive impedance for $f \approx 1$ kHz. It is shown that the capacitance and inductance of irradiated Schottky diodes (Mo/*n*-Si) depend on the concentration of the doping impurity (phosphorus atoms). The maximum specific inductance observed on diodes irradiated with α-particles, measured at frequency $f = 75$ Hz, is ≈ 2.5 H/cm^2. This far exceeds the typical value of ≈ 10 μH/cm^2 for flat metal film inductors.

It has been shown that three types of radiation-induced defects prevail in the diodes irradiated with α-particles: *A*-centers (a vacancy of a silicon atom in the crystal matrix and an oxygen atom), divacancies, and *E*-centers (a vacancy and a phosphorus atom). The latter are annealed at 150 °C for 30 min.

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