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GENERAL EXPERIMENTAL TECHNIQUES

A Compensation Method for Measuring the Junction Temperature of a p^+–p–n^+ Silicon Structure

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Abstract—The principle of determining the temperature of an active junction is considered. The method is based on measuring the temperature dependence of the forward bias voltage using the compensation method that provides the direct calibration of the junction temperature as a function of the bias voltage. An example of a microwave diode on a p^+–p–n^+ silicon structure is used to determine the dependences of the junction temperature on the magnitude of the flowing direct current and applied pulsed power with a variable frequency.

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INTRODUCTION

Such semiconductor devices as bipolar transistors, light-emitting diodes, voltage stabilizers, and microwave diodes are used in the mode of significant operating currents. Under such conditions, their durability, stability of parameters, reverse-current drift, breakdown voltages, and withstood powers directly depend on the operating temperature of the active junction. Therefore, it is necessary to know the junction temperature as a function of the operating conditions, especially as applied to semiconductor structures that operate with pulsed overloads. In contrast to numerous studies, e.g., [1–3], where the application of semiconductor devices with p–n junctions for determining the ambient temperature is considered, this study is devoted to studying the dependence of the temperature of a p–n junction on the liberated power under the action of a flowing direct current and a pulsed power with a variable frequency.

COMPENSATION METHOD FOR DETERMINING THE JUNCTION TEMPERATURE

The temperature of a p–n junction can be determined by measuring the crystal temperature. However, its value may differ from the temperature of the active region of the p–n junction. As applied to diodes and light-emitting diodes (LEDs), it is desirable to determine the temperature of p–n junctions from the calibration temperature dependences of the voltage drop across a forward-biased junction. This is due to

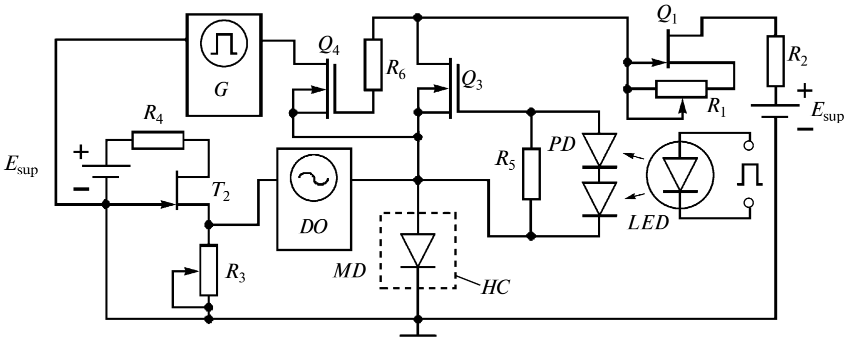

Fig. 1. Electronic circuit of the setup for measuring the p–n junction temperature: (*MD*) measured diode, (*LED*) light-emitting diode, (*HC*) heat chamber, (*PD*) photodiode, (*G*) generator, and (*DO*) digital oscilloscope.

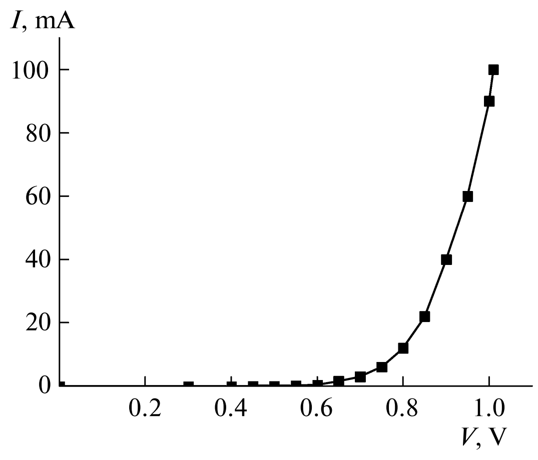

Fig. 2. The forward current–voltage characteristic of the *p*–*i*–*n* diode.

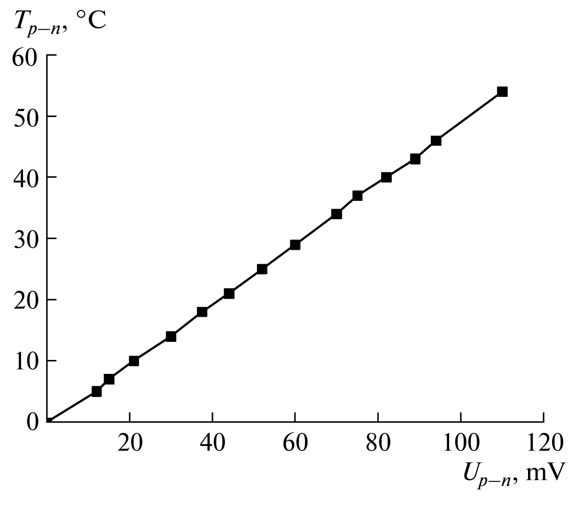

Fig. 3. The dependence of the junction temperature on the voltage drop.

the fact that in the forward-bias mode of a *p*–*n* junction in the region of currents that are comparable to a reverse current, the voltage across a *p*–*n* junction is a linear temperature function and is predominantly determined by the temperature dependence of the base-region energy-gap width [4]:

$$\frac{dV_f}{dT} = \frac{eV_f - E_g}{eT} + \frac{1}{e}\frac{dE_g}{dT} - \frac{3k}{e},$$

where V_f is the forward voltage drop, e is the electron charge, E_g is the energy-gap width, T is the temperature, and k is the Boltzmann constant.

In the presented method, we measure the difference between the voltage determined at an initially specified temperature and the voltage across a *p*–*n* junction at the temperature that is produced by heating. Thus, this is a compensation method.

The method for determining the temperature of a *p*–*n* junction is as follows. A forward voltage from one current source is applied to a diode that is placed in a heat chamber. A voltage that is equal to the voltage drop across the *p*–*n* junction is formed across the load of the second current source, and the temperature-dependent difference of the voltages across the load and across the *p*–*n* junction is measured for reference points. The curve thus obtained is assumed to be the calibration curve for the investigated diode.

Subsequently, the investigated diode is switched to the high-heat-liberation mode and after a thermal equilibrium establishes, the diode returns to the temperature-measurement mode. The calibration curve is used to determine the temperature of a given effect (a current or a power pulse).

The high-current-action mode is switched to the temperature-measurement mode using an electronic switch, which is controlled with a light pulse (Fig. 1). The setup for measuring the temperature of a *p*–*n* junction consists of two units: a compensation measurement unit based on field-effect transistors (FETs) Q_1 and Q_2 and a high-speed electronic-switch unit on two metal–oxide–semiconductor (MOS) transistors Q_3 and Q_4.

A voltage from power supply E_{sup} is fed through Q_1, whose current is controlled with resistors R_1 and R_2, to the channel of the MOS transistor Q_3 and to the gate of the MOS transistor Q_4. If a control pulse from the light-emitting diode (LED) *LD* arrives at the FET gate, a photodiode *PD* produces a voltage that opens the channel and a current is fed to the measured diode *MD* (placed in the heat chamber *HC*), whose terminal is connected to the source of the MOS transistor Q_4 and to the oscilloscope. In this case, the voltage that drops across the measured diode and corresponds to the zero temperature in the chamber is compensated by a voltage that is fed from transistor Q_2. The temperature in the chamber then increases with a certain step for calibration, and readings are taken as calibration values.

At the next stage, when the control light pulse is switched off, the channel of the MOS transistor Q_3 is shut and the voltage is fed to the gate of the MOS transistor Q_4. The Q_4 channel changes to the conducting state, and a pulse current from the generator is fed to the studied diode and heats its *p*–*n* junction.

Microwave diodes on the basis of p^+–p–n^+ structures were studied. Such diodes were chosen because their base thickness is 250–500 μm; therefore, the diode turning-on time in the measurement mode is shorter than the heat-flux relaxation time. In addition, the electronic switch is characterized by shorter transient switching processes than the repetition period of switching pulses [5].

The developed method is used to plot the temperature dependence of the voltage drop across the p^+–p–

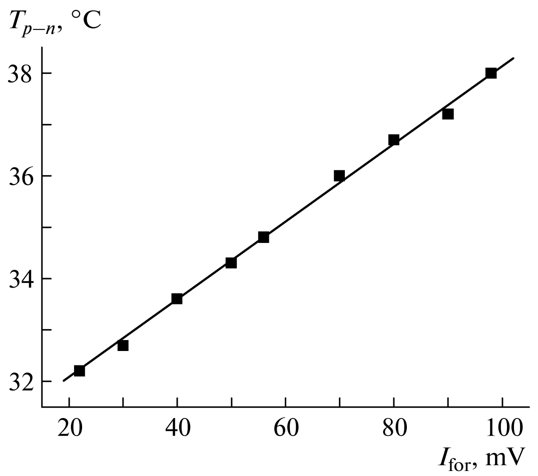

Fig. 4. The dependence of the p^+–p–n^+ junction temperature on the forward direct current.

n^+ junction. For this purpose, as applied to the studied p^+–p–n^+ structure, the operating voltage across the diode, which is supplied from the current source, is chosen in the initial segment of the diode current–voltage characteristic (CVC), i.e., <0.4 (Fig. 2), where the currents are $<10^{-4}$ A/cm^2. As the temperature in the thermostat increases, the voltage drop decreases and the voltage difference increases.

The junction temperature was determined when a forward current passed through the p^+–p–n^+ junction (Fig. 1) and the LED was turned off. After the current that passed through the diode got stabilized, the LED was turned on by a pulse and the voltage drop across the p–n junction was measured. The diode was then placed into the heat chamber with a specified initial temperature T_0. A value of the forward voltage drop across the junction was set using the resistor R_1 and concurrently compensated by a voltage that was fed from the stable-current source and controlled with the resistor R_3. In this case, the LED was enabled and the channel of the MOS transistor Q_3 was in the conducting state (Fig. 1). After that, the dependence of the voltage drop on the specified fixed temperatures $U = f(T)$, which was exactly the calibration curve, was measured.

EXPERIMENTAL RESULTS AND DISCUSSION

Figure 4 shows the dependence of the p–n junction temperature on the forward current, which was determined using the above-described method. According to Fig. 4, when a forward current of 20–100 mA flows, the junction temperature for this specimen linearly increases from the initial T_0 to 38°C.

In addition, the temperature distributions over the diode case were investigated via direct temperature measurements (using a built-in thermocouple) of the diode case and the upper contact in the form of a ball connected to the n-type region [6] (Fig. 5). These studies showed that, when a pulsed power is fed, the junction temperature first increases owing to the released power, and then heat propagates through the case to the environment. According to Fig. 5b, the diode-case temperature is lower than the p–n junction temperature and, as the pulsed power increases, the temperature difference increases as well.

Because the studied diodes are intended for operation in the pulsed mode, the dependences of the p–n junction temperature on the applied pulsed power were studied (Fig. 6). The duration of rectangular pulses was 2.5 μs. The pulse repetition rate was $f = 8$ Hz at an off-duty factor of $Q = 50\,000$, $f = 40$ Hz at $Q = 10\,000$, and $f = 400$ Hz at $Q = 1000$.

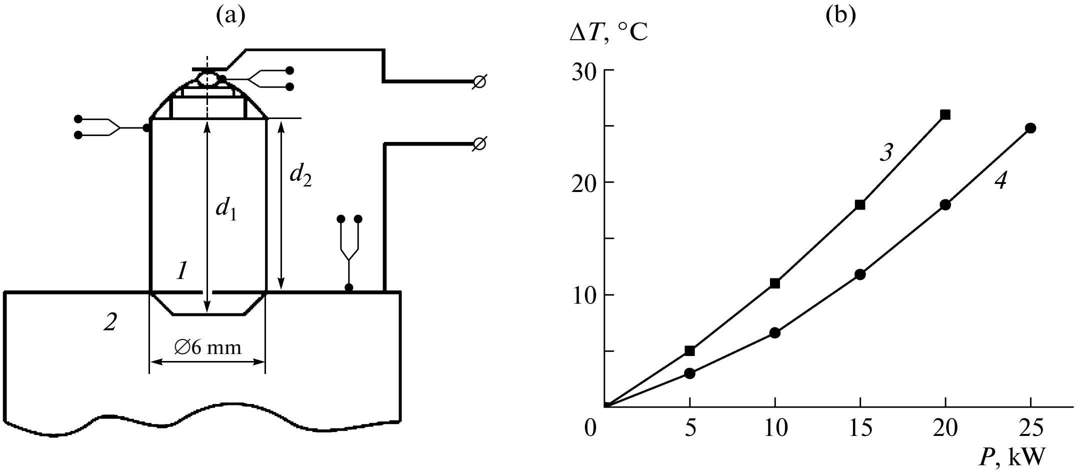

Fig. 5. (a) A schematic diagram of the studied p^+–p–n^+ silicon diode structure: (*1*) silver-plated copper diode case and (*2*) base for fixing the diode; (b) the dependences of the p–n junction and case temperature increments on the incident pulsed power.

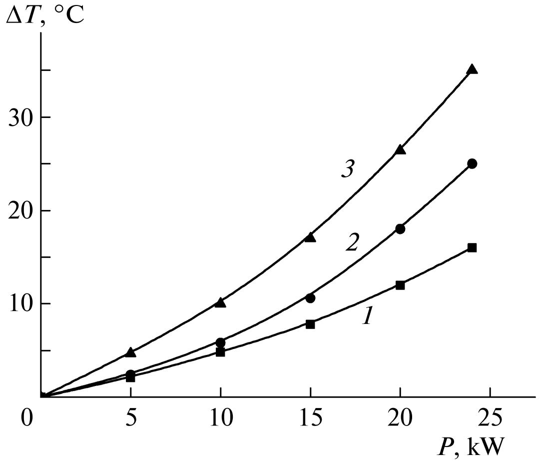

Fig. 6. The dependences of the junction temperature on the applied pulsed power for different pulse repetition rates: (*1*) 8, (*2*) 40, and (*3*) 400 Hz.

According to Fig. 6, the junction temperature increases with an increase in the pulse repetition rate for given powers. The average energies for curves *2* and *3* are five and ten times higher, respectively, than that for curve *1*. The observed dependences (Fig. 6) indicate that the heat removal becomes efficient at higher average energies.

A nonlinear temperature increase is observed with an increase in the applied pulsed power.

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