Vector Analysis of Electrical Networks for Temperature Measurement of MOS Power Transistors

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Abstract: The article presents the concept of using VNA (Vector Network Analyzer) to measure the temperature of the MOS transistor junction. The method assumes that the scattering parameters of the network consisting of the transistor depend on the temperature. The tests confirmed the influence of temperature on the S_{11} parameter and the input network capacity during ambient temperature changes in the range of 35–70 °C. Measurements were made for the gate-source (G-S) input of the system. The measurements were carried-out with the transistor in the ON/OFF states. In order to validate the measurements, the temperature of the tested element was recorded with the MWIR Cedip-Titanium thermal imaging camera.

Keywords: Vector Network Analyzer, IR camera measurement, S-parameter, MOS transistor, electrical impedance

1. Introduction

Measurement of the internal temperature of semiconductor power devices is normally performed with an additional temperature sensor integrated with DUT (Device Under Test). In the case of bipolar transistors (BJT), the base-emitter diode can be used to measure the temperature. Power MOS transistors have a parasitic p-n technological diode, which can be used as a temperature sensor [2, 3] when the transistor is turned off. Such a measurement requires the application of a low-value current source connected in an appropriate state of operation of a transistor [4].

For MOS transistors, the ON-state resistance R_{on} of the channel varies with temperature and current [1]. There were attempts to use R_{on} resistance to measure the internal temperature of DUT. Most of the proposed measurement methods are off-line ones, recommended for manufacturers of semiconductor devices for the verification of production quality or for system developers for the selection of appropriate components. There is a commercially available system for monitoring the internal temperature of semiconductor elements, based either on an integrated p-n junction or on an external temperature sensor to measure temperature [12].

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In the field of high frequency and microwave electronic circuits, the vector analysis approach is very useful. Until now, such systems were intended rather for laboratory applications [5]. Currently, there are portable and handy Vector Network Analysers with acceptable technical specifications for various applications [6, 7]. Such measurement systems power the DUT and measure the electrical response over the wide frequency range, sometimes up to GHz. The results can be presented in the form of frequency dependent electrical impedance/admittance, but in most cases they provide scattering (S) parameters very useful in the development of microwave and antenna circuits [8–10].

There is a need to measure the temperature of the semiconductor structure of power devices that do not have any p-n junction inside, e.g. GaN transistors. This research is devoted to such applications and can be applied to AC and DC converters equipped with such modern elements. The main research hypothesis presented in the article is the possible use of the VNA and scattering parameters S to monitor the temperature inside power semiconductor devices.

The power MOS transistor contains parasitic capacitances between all electrodes (Fig. 1). These capacitors correspond to the input, output and feedback capacitances (C_{iss}, C_{oss}, C_{rss}) measured by the manufacturers and reported in application notes [13].

The dependence between to the input, output and feedback capacitances C_{iss}, C_{oss}, C_{rss} and the physically existing ones C_{gs}, C_{gd}, C_{ds}, can be expressed by eq. (1) and (2) [11].

$$C_{iss} = C_{gs} + C_{gd}$$

$$C_{rss} = C_{gd} \tag{1}$$

$$C_{oss} = C_{ds} + \frac{C_{gd}C_{gs}}{C_{gd} + C_{gs}} \quad C_{ds} = C_{oss} - \frac{C_{rss}\left(C_{iss} - C_{rss}\right)}{C_{iss}} \tag{2}$$

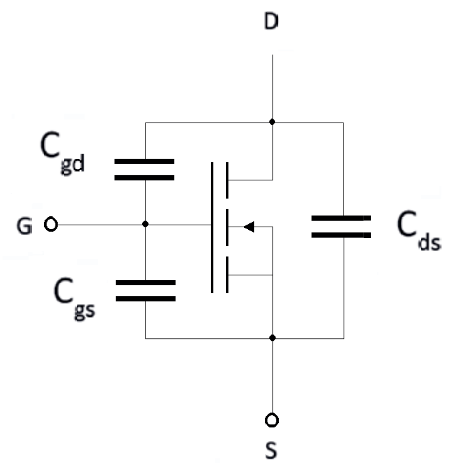

Fig. 1. Parasitic capacitances of MOS transistor
Rys. 1. Pojemności pasożytnicze tranzystora MOS

The developed method and the results obtained confirm the validity of the concept of a new approach to measure the temperature of electronic devices with the use of VNA. However, the authors treat them as preliminary results that should be carefully analysed during the further research.

2. Measurement setup

For the research presented in this paper, the n-channel enhancement mode IRFZ44N Trench MOS transistor was selected. For this transistor, input capacitance C_{iss} = 1350–1800 pF, output capacitance C_{oss} = 330–400 pF and feedback capacitance C_{rss} = 155–215 pF, measured for V_{GS} = 0 V, V_{DS} = 25 V and for f = 1 MHz. The similar electrical conditions were selected for the measurements during this research.

In order to verify the influence of ambient temperature changes on the tested MOS transistor IRFZ44N in the TO220AB housing, a BINDER ED 115 heating chamber was used. The DUT device was affected by natural convection anly. The temperature range of the chamber is T_{HEAT} from 5 °C above ambient temperature to 300 °C. The inspection opening made by the manufacturer in the upper part of the heating chamber allowed for recording the S_{11} parameters using portable VNA. A portable, inexpensive VNA was used for measurements. The device has a frequency range of 50 kHz–1500 MHz and the maximum output power of –9 dBm.

At the same time, temperature changes on the tested transistor were monitored with the Cedip-Titanium MWIR (Medium Wave Infrared Range) camera through the another inspection opening in the side wall of the heating chamber. The IR camera is characterized by high recording speed up to 1000 frames per second. The thermal resolution of the camera is NETD < 18 mK, and the cooled InSb matrix contained 640 × 512 pixels. The signals recorded by the VNA and IR cameras were saved in the computer memory for the detailed analysis (Fig. 2).

The measurement was based on heating the chamber in the range of 35–70 °C. The S_{11} parameter value changes were registered using a portable VNA every 5 °C of T_{HEAT} in the steady. The signal generated by the internal Si5351 oscillator built into the VNA was connected to the gate-source (G-S) pins of the tested MOS transistor (Fig. 2). The frequency range of the signal recorded by the VNA was 50 kHz–20 MHz. Measurement data was collected with the software installed on the notebook. At the same time, the T_{MOS} temperature was recorded by the IR camera with a sampling frequency of 100 Hz (Fig. 3). Additionally, measurements were made for either ON or OFF state of the tested device. The electrical conditions for these measurements were: V_{GS} = 0 V(OFF)/10 V(ON) and V_{DS} = 20 V. The collected data was analyzed in order to estimate changes in the values of selected parameters as the function of the ambient temperature T_{HEAT} and T_{MOS}.

Before the measurements, a simple simulation of the transistor's operation was carried out at the ambient temperature T_a = 25 °C using the LTspice XVII program. The schematic diagram of the modeled circuit is shown in Fig. 4. In order to make the model compatible with the experiment, the series inductance L_1 was added to the gate connection (Fig. 4). It corresponds to the inductance of the wire several cm long used in the experiment. Switching the transistor was achieved by changing the value of the resistance R_1 from a few MΩ to 10 kΩ.

Voltage source V_2 simulates the VNA generator. Changing the frequency of this generator allows to estimate the impedance character of the measured device. Due to the LC series branch, at lower frequency values the impedance between gate and ground starts from capacitive to resonance at frequency around 10 MHz. For higher frequencies, the input circuit becomes inductive. This simulation result is in line with the experimental result obtained by the VNA.

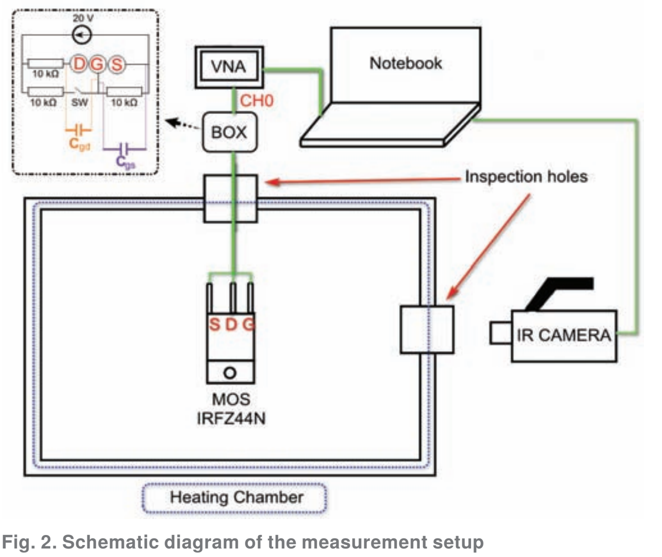

Fig. 2. Schematic diagram of the measurement setup
Rys. 2. Schemat ideowy stanowiska pomiarowego

Fig. 3. Measurement setup with the heating chamber, VNA and IR camera
Rys. 3. Stanowisko pomiarowe: komora grzewcza, VNA oraz kamera IR

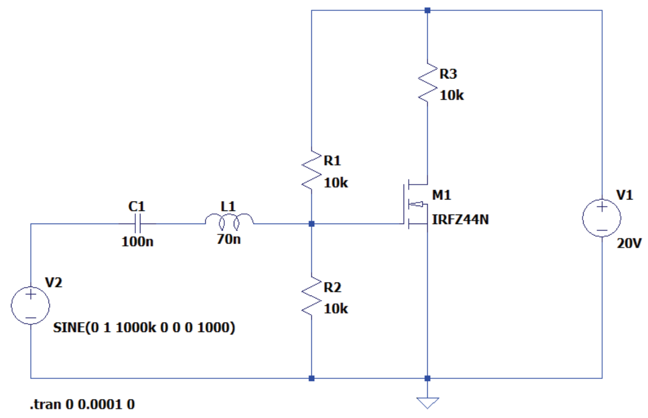

Fig. 4. The schematic diagram of the simulated circuit
Rys. 4. Schemat elektryczny symulowanego obwodu

3. Experimental results

Figure 5 shows the measured Smith chart representing the changes of S_{11} parameter value. The measurement of the selected parameters were performed for the frequency corresponding to $-\pi/2$ phase shift of S_{11} parameter. Experimentally, two values of excitation frequency were selected $f_1 = 1.0475$ MHz and $f_2 = 0.848$ MHz for which the phase shift is close $\phi \approx -\pi/2$, indicated in Fig. 5. According to the concept of new application of VNA and theoretical considerations, the input capacitance were analyzed. The circular shape of S_{11} in the Smith diagram confirms the almost pure capacitive character of the input circuit measured between the gate and the source electrode of the MOS transistor. Due to the series inductance, the character of the circuit changes to inductive above the frequency $f > 10$ MHz.

The sensitivity of the measured parameters is high, which results from the characteristic of the phase shift (Fig. 6). A significant and steep slope of the characteristic is for $\phi \approx -\pi/2$. Negative phase shift values are related to the capacitive character of the internal in-build transistor structure. For this measurement condition, the high thermal sensitivity is expected. The obtained values of input capacitance C_{in} for both considered frequencies were averaged and the relation $C_{in} = f(T_{MOS})$ was determined for ON and OFF states of DUT. The obtained numerical results of the measurements are presented in Table 1. The temperature in the heating chamber can only be set above the ambient temperature. Therefore, a starting temperature of 35 °C was selected.

The measurement system was developed to reduce or nearly eliminate self-heating of a transistor (Figures 2 and 4). This is due to the small value of the drain current of several mA. Analyzing the data presented in Tables 1, it can be seen that the ambient temperature T_{HEAT} set by the heating chamber corresponds linearly to the temperature T_{MOS} measured by a thermal imaging camera. However, there is a difference between the T_{EAT} and T_{MOS} temperatures due to the nonhomogeneous temperature distribution and the long settling time in the heating chamber. Nevertheless, the T_{MOS} takes almost the same value for both measurements, regardless of the transistor state ON/OFF. This is confirmed by the lack of self-heating effect of the transistor in the ON state.

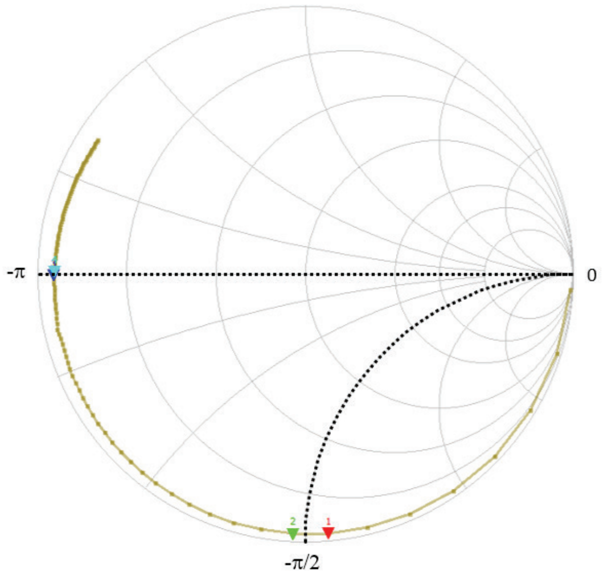

Fig. 5. Example of the S_{11} parameter changes for frequency range $f \in (0.05, 20)$ MHz
Rys. 5. Przykład zmian parametru S_{11} w zakresie częstotliwości $f \in (0.05, 20)$ MHz

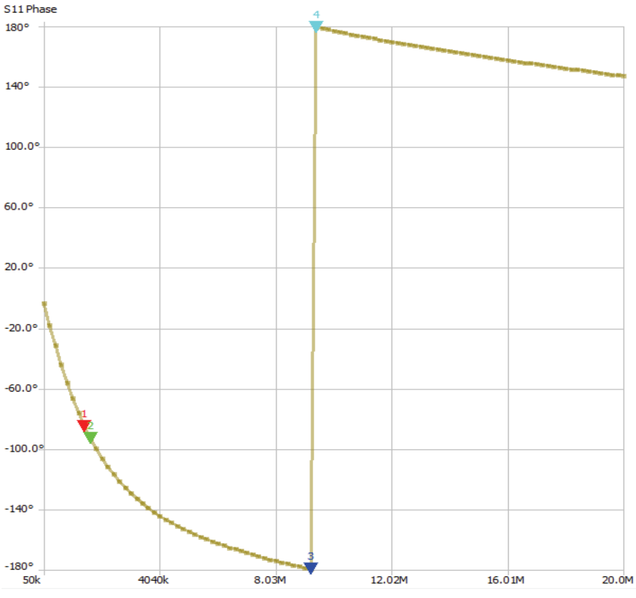

Fig. 6. Example of the phase change characteristic of S_{11} parameter (1st and 2nd marker – $\phi \approx -\pi/2$; 3rd marker $\phi \approx -\pi$, 4th marker $\phi \approx \pi$)
Rys. 6. Przykładowa charakterystyka zmiany przesunięcia fazowego parametru S_{11} (1, 2 marker – $\phi \approx -\pi/2$; 3 marker $\phi \approx -\pi$, 4 marker $\phi \approx \pi$)

Table 1. Summary of changes in the series capacitance Cin versus temperature T_{MOS} and T_{HEAT} for ON and OFF states of DUT
Tabela 1. Zestawienie zmian pojemności Cin względem temperatur T_{MOS} oraz T_{HEAT} dla stanu pracy ON/OFF

T_{HEAT} (°C)	GS_{OFF}		GS_{ON}	
	T_{MOS} (°C)	C_{in} (nF)	T_{MOS} (°C)	C_{in} (nF)
35.00	33.67	3.11610	33.81	3.15025
40.00	41.06	3.11305	40.45	3.14640
45.00	47.59	3.11045	47.43	3.14350
50.00	54.37	3.10895	53.40	3.14100
55.00	61.43	3.10620	60.74	3.13865
60.00	66.56	3.10470	66.89	3.13645
65.00	71.13	3.10340	71.73	3.13500
70.00	76.10	3.10150	76.11	3.13205

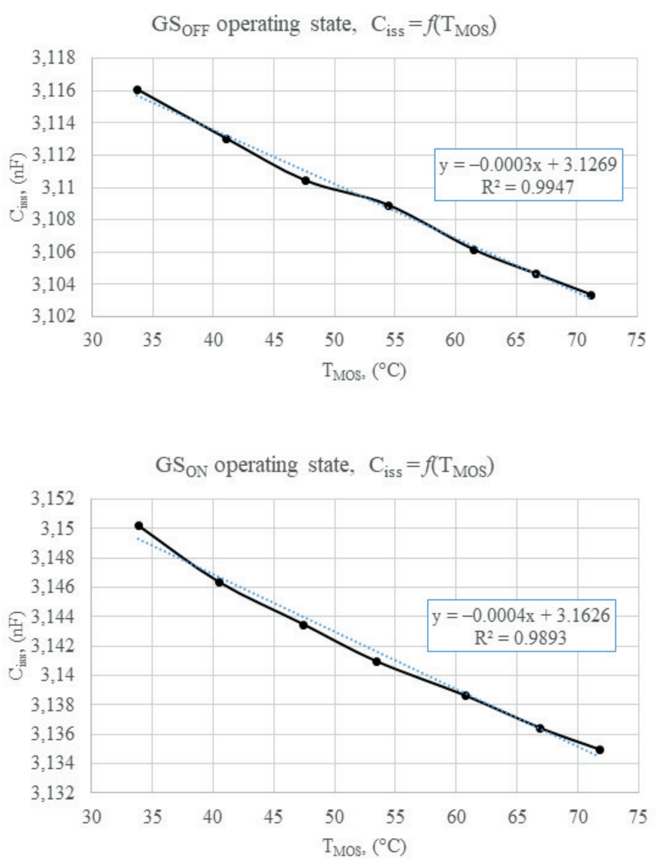

Fig. 7. Dependence of C_{iss} capacitance as a function $C_{iss} = f(T_{MOS})$, for ON and OFF state of N-channel enhancement mode IRFZ44N TrenchMOS transistor

Rys. 7. Zależność pojemności C_{iss} w funkcji $C_{iss} = f(T_{MOS})$ dla tranzystora, w stanie pracy ON/OFF – IRFZ44N TrenchMOS z kanałem typu n

These changes of T_{MOS} temperature varies the series capacitance for both measurements setup (ON/OFF).

The values of the input capacitance in both states are very similar. For the ON state of the input capacitance of the transistor it is slightly larger due to the bypassing of the drain capacitance. The input capacitance decreases with temperature as shown in Fig. 7.

The input capacitance depends on the ambient temperature and the operating state of the transistor. After averaging the value of the input capacitance for 2 adjacent frequencies near the phase of S_{11} equal to $-\pi/2$, the input capacitance changes by –16.4 pF with increasing temperature T_{MOS} from 33.67 °C to 76.10 °C.

The nearly linear characteristics of capacitance change as a function of temperature T_{MOS} exhibit the sensitivity of capacitance variation versus temperature as in eq. (3).

$$\frac{\partial C_{in}}{\partial T_{MOS}} = -0.39 \frac{\text{pF}}{°\text{C}} \tag{3}$$

4. Conclusions

The use of the VNA as a measuring device for S_{11} parameter allows the determination the impedance character of the electrical network consisting of a MOS transistor. Electrical parameters were measured for the appropriate frequency. As the temperature of the transistor increases, the input capacitance decreases.

The temperature T_{MOS} ranged from 33.67 °C to 76.10 °C. The temperature set by the control system of the heating chamber T_{HEAT} was slightly higher. An increase in T_{MOS} temperature by approximately 40 °C caused a capacity decrease by approximately 16 pF. This means that the average sensitivity of capacitance changes as a function of temperature is –0.39 pF per 1 °C for the temperature T_{MOS} measured with the IR camera.

The obtained results of these preliminary studies confirmed the correctness of the new approach to monitor static and dynamic temperature changes inside the structure of MOS transistors with the use of S_{11} parameter. The application of the VNA to measure temperature changes requires calibration for each test object to determine the frequency for phase of S_{11} equal to $\phi \approx -\pi/2$. Presumably, adjusting an appropriately narrow frequency range for analysis will increase the accuracy of the measurement and eliminate the fluctuations of capacitance changes visible in the obtained results (Fig. 7).

The obtained results are too early to provide clear evidence and exact dependencies for the new measurement method of junction temperature of MOS transistors. The research requires further works and the development of a dedicated measuring system in order to increase the precision and sensitivity of the registered changes in series capacitance and the temperature of the transistor's internal structures. In particular, an uncertainty analysis will be performed to confirm the practical suitability of the proposed method. However, preliminary research and the results presented are promising.

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Zastosowanie analizy wektorowej sieci elektrycznych do pomiaru temperatury tranzystorów MOS

Streszczenie: W artykule przedstawiono koncepcję wykorzystania wektorowego analizatora sieci VNA (ang. Vector Network Analyzer) do pomiaru temperatury złącza tranzystora MOS. Metoda zakłada, że parametry rozpraszania sieci elektrycznych wewnętrznych struktur tranzystora zależą od temperatury. Badania potwierdziły wpływ temperatury na parametr S_{11} oraz na pojemność wejściową przy zmianie wartości temperatury otoczenia w zakresie 35–70°C. Pomiary wykonano dla wejścia bramka-źródło (G-S) układu. Pomiary przeprowadzono z tranzystorem w stanach ON/OFF. W celu walidacji pomiarów, temperaturę badanego elementu rejestrowano kamerą termowizyjną MWIR Cedip-Titanium.

Słowa kluczowe: VNA, Wektorowy Analizator Sieci, temperatura, parametry rozpraszania, parametry S, tranzystor MOS, impedancja elektryczna, pomiary termowizyjne

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