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DEVELOPMENT OF A SYSTEM FOR THERMAL EVAPORATION

Annatation. The simulation of the thermal evaporation was considered. For this purpose, a hardware system was constructed for research of thermal vacuum evaporation and the phenomena arising in it.

Keywords: vacuum, step down converter, buck, thermal vacuum evaporation.

Introduction and statement of the problem

To conduct research in the field of creating functional coatings, mentioned in [3,4], was required a source with stable output parameters, low noise and with the possibility of smooth adjustment.

For thermal evaporation of metal in vacuum, was needed adjustable power source capable of delivering a sufficiently high current (usually 25-50 A) and a low voltage of 1-5 Volts. This source is needed to heat the boiling type evaporator of molybdenum or titanium, resistance of which can be from 0.05 - 0.5 Ohm.

Goals

The main purpose of this work is development hardware system for thermal evaporation in vacuum.

The main part

One of the solutions to this problem can be a buck topology converter. This type of converter has become an integral part of modern electronics. Step down converters of this topology are used to power the computer processor. Requirements for the current and voltage of the processor are similar to those required for thermal evaporation.

Buck converter topology includes a “switch” in the form of a field effect transistor, a Schottky diode, a storage coil, as well as a pair of capacitors (Fig.1). In the case of a synchronous buck converter, the diode is replaced by another transistor, which dramatically increases the efficiency, since the fall at the junction of the transistor is much less than on the Schottky diode.

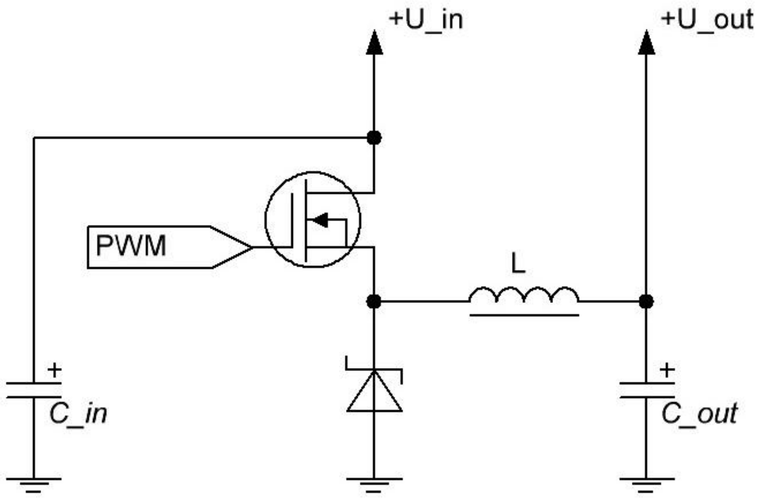

Figure 1 – Topology of step down buck converter

Despite the lower efficiency of the asynchronous converter, it has advantages in the form of simplicity and lower output noise. In synchronous converters, the output noise is caused by bi-directional current flow. For research tasks, low output noise plays a key role.

The most critical element of this circuit is a power coil, the efficiency, the possibility of outputting large currents, voltage ripple at the output depends on its correct calculation. In our case, the frequency converter is fixed and equal to 100 kHz, control will be done using PWM, the coil will be in continuous current mode (PHT). This mode is characterized by the fact that at the moment when the field effect transistor is closed, the coil is not fully discharged into the load. The equation below is true for an ideal transistor and a diode, the transfer resistance and the switching speed of the transistor (1) are not taken into account:

$$L = (V_{in} - V_{out}) \cdot \frac{V_{out}}{V_{in}} \cdot \frac{1}{f_{sw}} \cdot \frac{1}{0{,}3 \cdot I_{out}}, \qquad (1)$$

where f is the switching frequency of the transistor. The coefficient 0.3 is responsible for the ratio of efficiency and response to varying loads. With an input voltage of 12 volts, maximum output of 5 volts and a rated current of 50 A, we obtain an coil inductance of ~ 10 μH. To determine the maximum saturation current responsible for the dimensions of the coil, we use the formulas below (2, 3):

$$I_{peak} = I_{out\,\max} + \frac{\Delta I_{inducor}}{2}, \qquad (2)$$

$$\Delta I_{inductor} = \frac{1}{L} \cdot \frac{1}{f_{sw}} \cdot \frac{V_{out}}{V_{in}} \cdot (V_{in} - V_{out}). \qquad (3)$$

For the previously obtained inductor, the saturation current will be about ~ 51.5 Amperes, we take a margin of 25% from the calculated nominal.

For suppressing high-frequency pulsations caused by switching the field-effect transistor, the load behavior, parasitic oscillations, etc., are answered by the output capacitor of the converter (C_out). To determine the minimum required output capacity, we use equation (4):

$$C_{out} = \frac{L \cdot (I_{out\,\max} + \frac{\Delta I_{inductor}}{2})^2}{(\Delta U + U_{out})^2 - U_{out}{}^2}. \tag{4}$$

Taking the value of the maximum overshoot voltage of 100 mV, the input maximum voltage of 13 volts and the maximum output current of 50 Amps, we obtain the estimated capacitance ~ 6300 μf, the nearest standard nominal 6800 μf.

To calculate the output ripple at this capacity, we use the formula (5):

$$U_{ripple} = \frac{1}{2 \cdot C} \cdot \frac{U_{in} - U_{out}}{L} \cdot (\frac{U_{out}}{U_{in}} \cdot \frac{1}{f_s})^2 + \Delta I_{inductor} \cdot ESR_C\,. \tag{5}$$

When the frequency of the converter is 100 kHz and the capacitance of the output capacitor is 6800 μf with ESR = 0.24 Ohm, we get pulsations > 20 mV.

However, in practice, in spite of the correct calculation of the choke and the output capacitor, high-frequency oscillations appear, visible with an oscilloscope. These fluctuations are a very harmful phenomenon, they cause overvoltage, which can lead to the opening of the lower key (in the case of a synchronous buck converter), can cause damage to the components of the load, high-frequency oscillations can introduce errors in the feedback, as well as interfere with accurate measurement of the output current and voltage buck converter (Fig.2).

To decrease spurious oscillations, a number of methods are used: reducing the initial pulse energy, reducing the parasitic inductance of the circuit, reducing the parasitic capacitance of the circuit (C_stray), and also using the snubber circuit. Due to the complexity of the implementation of other methods, let us dwell on the latter.

The magnitude of the parasitic inductance is extremely small, but with a rapidly changing and high current, it creates large amplitudes of emissions. Parasitic capacitance - is the capacitance between the anode and the cathode of the Schottky diode, the capacitance between the drain and the source of the transistor, the mounting capacitance. Due to the small values of these parasitic elements, the frequencies become very large, for example, 18 MHz (Fig.3).

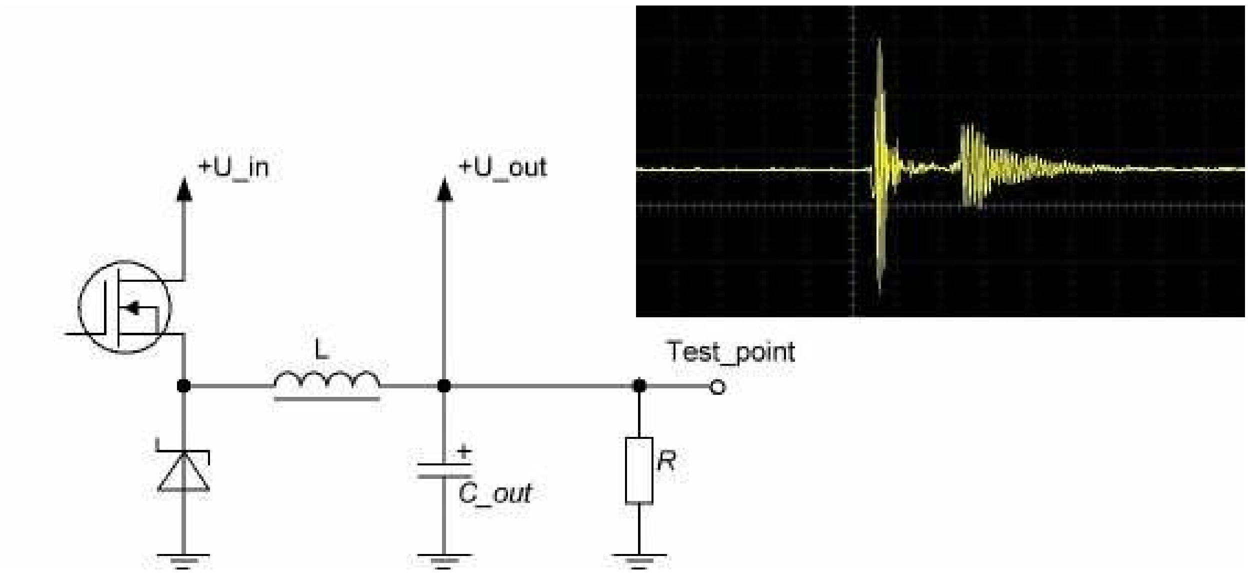

Figure 2 – Parasitic oscillations on output of buck converter

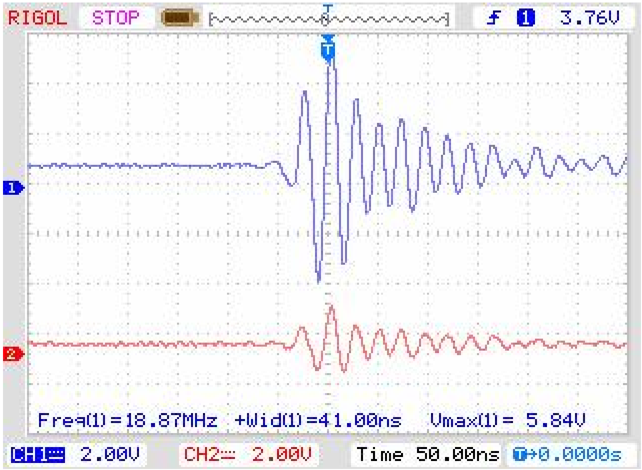

Figure 3 – Parasitic oscillations on the output of buck converter

The magnitude of the parasitic inductance can be found by calculation. To do this, measure the frequency with an oscilloscope. In our case, it was approximately 18 MHz. Using the Thomson formula (6) we find the parasitic inductance (7).

$$f = \frac{1}{2 \cdot \pi \cdot \sqrt{L \cdot C}} \tag{6}$$

$$L = \frac{1}{4 \cdot \pi^2 \cdot f^2 \cdot C} \tag{7}$$

Based on the technical documentation, the parasitic capacitance was ~ 200 pF, which at 3 MHz will give us a parasitic inductance ~ 7 µH.

With the parasitic capacitance and inductance values, the snubber circuit can be calculated. The simplest snubber is a circuit of a series-connected resistor and a capacitor. The snubber resistor rating is calculated based on the fact that the optimal resistance of the resistor must be equal to the characteristic impedance of the oscillating circuit (8).

$$R = \sqrt{L / C} \qquad (8)$$

Substituting the resulting parasitic capacitance and inductance into this equation, we obtain a resistance of ~ 187 Ohms, the closest resistance from the E24 series is 180 Ohms.

The snubber capacitance value is selected based on efficiency. As each cycle, the capacitance is recharged and dissipates thermal power through a resistor. A correctly calculated snubber should reduce the efficiency by no more than 1 - 2%. In practice, the snubber value is determined from the condition that the snubber time constant should be 3 or more times longer than the period of parasitic oscillations (9):

$$R \cdot C = 3 \cdot T = \frac{3}{f}, \qquad (9)$$

where T and f is the period and frequency of spurious oscillations. Based on this, the snubber's capacity can be found by the formula (10):

$$C = \frac{3}{R \cdot f} \qquad (10)$$

Substituting the value of the snubber resistance already found into 180 Ohms, we find the capacitance, it will be ~ 5 nF.

Knowing the capacitance and resistance of snubber, the voltage that is fed to the input of the converter, as well as the switching frequency of the field-effect transistor, we can find the thermal power that is dissipated on the snubber when extinguishing parasitic oscillations, for this we use formula (11).

$$P = \frac{1}{2} \cdot C \cdot U^2 \cdot f_s, \qquad (11)$$

where U is the voltage applied to the input of the converter, f is the frequency of operation of the converter. With a frequency converter of 100 kHz, an input voltage of 12 volts and a capacitor capacity of 5 nF ~ 1 watt is dissipated into heat.

After installing the snubber circuit in the circuit, the pulsations decreased dramatically, there are still some noises under a load of 10 Amp, but they are negligible in amplitude (only 70 - 100 mV) and in frequency compared to what was without the snubber (Fig.4).

Since the converter is powered by an external 360-watt and 12-volt power supply, it makes sense to protect its OS from noise, even if it is not large, to do this, a choke equal to 1/3 of the inductance of the working choke is installed to break the positive bus of the converter. In our case, the closest at par 3.3 mH.

All electrolytic capacitors on the converter board are shunted by 2 ceramic capacitors of 10 nF and 100 nF. These measures allow to further reduce noise, up to 50 mV.

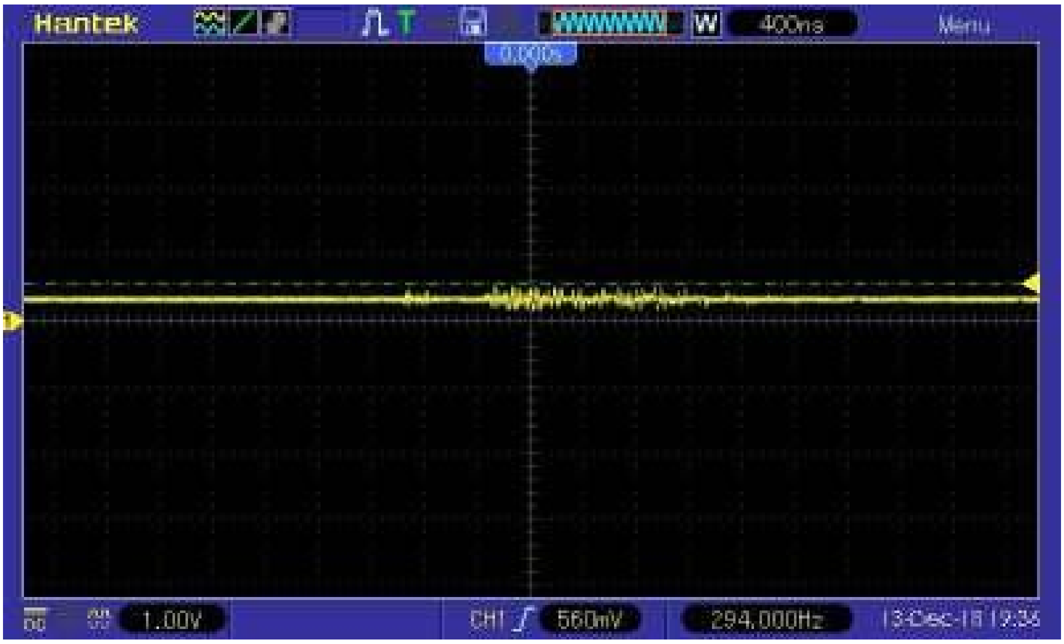

Figure 4 – Reducing the frequency and amplitude of spurious oscillations when using the calculated snubber

Of great importance to the efficiency of the converter is how the field effect transistor is controlled. Any field-effect transistor does not open immediately, at first the gate capacitance is charged to the threshold voltage specified in the transistor documentation, and then the Miller effect, which facilitates opening the key, is activated. In the first stage, the law of charge capacity through resistance, in the second PIC through the capacity of Miller.

In practice, the current required to control the field effect transistor can be calculated using the formula below (12).

$$I_{sw} = \frac{U_{open} \cdot C_{gate}}{t_{open}} \qquad (12)$$

For the IRFP3205 transistor, which is used in the circuit, the maximum driver current turned out to be ~ 0.87 A. Based on this current, we collect a driver capable of delivering such a current at a frequency of 100 kHz, with a margin of 20% (Fig.5).

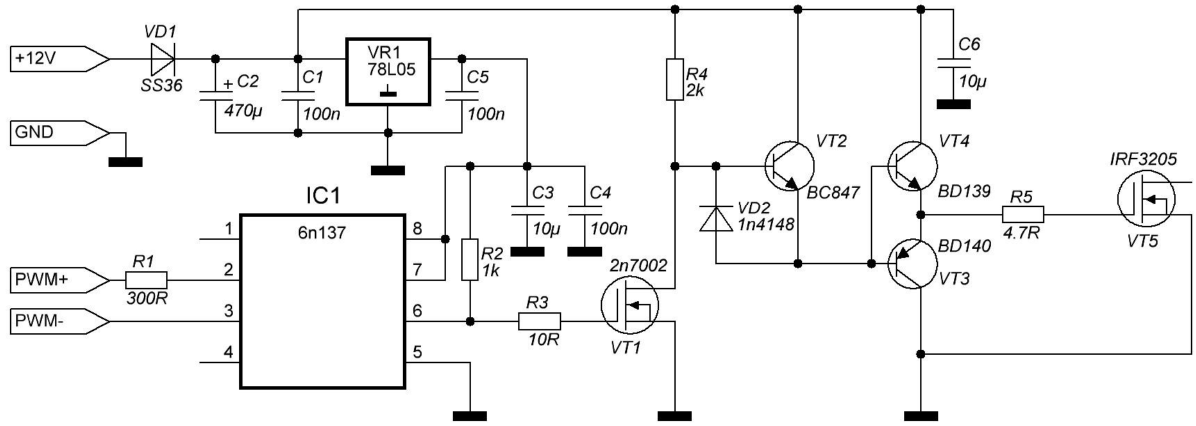

Figure 5 – Scheme of developed driver

The emitter follower of a complementary pair of bipolar transistors (VT3, VT4) is responsible for the output current, the npn transistor and the Schottky diode (VT2, VD2) are responsible for accelerating the opening of the transistor, and the field-effect transistor with a resistor (VT1, R4) is responsible for inverting the signal from the optocoupler. The optocoupler not only decouples the signal, but also aligns the fronts of the control signal, due to the built-in Schmidt trigger. Capacitors on the board are like power filters. It is worth mentioning that the driver power is not tied to the power supply, due to the characteristics of the control of the transistor in the upper arm.

Acceleration of the opening of the field-effect transistor is necessary in view of the reduction of the duration of the front, the smaller the switching time of the transistor, the less heat is generated on it. Due to the front too overwhelmed, the transistor may burn out. On the oscillogram (Fig. 6), the signal from the gate of the operating transistor at a load of 20 Amp is removed, because of the load, the ringing appears, the front decay ~ 110 ns.

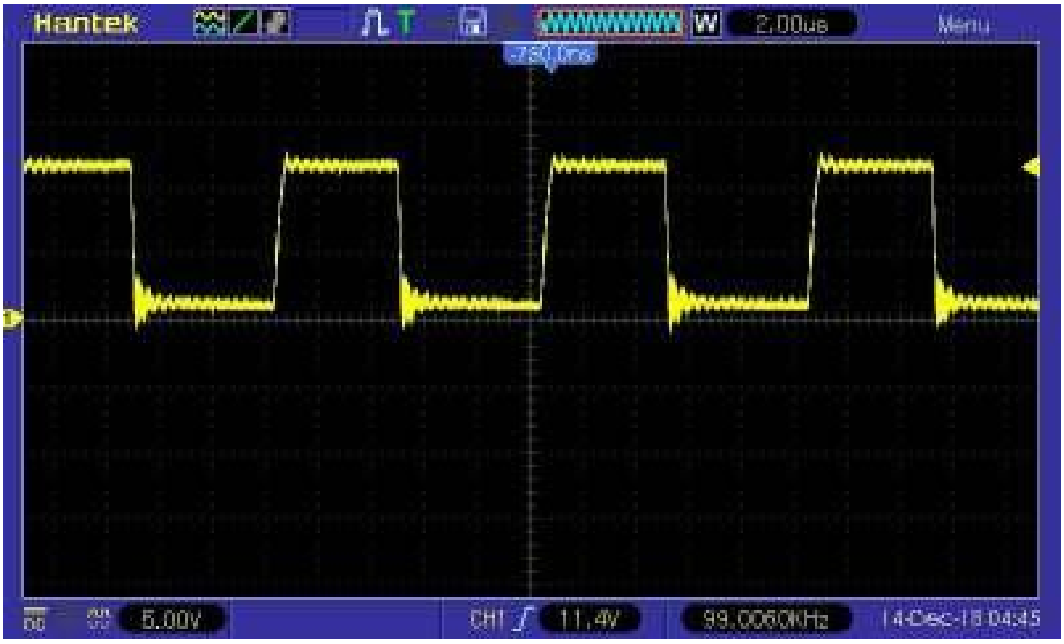

Figure 6 – The signal on the gate of the field-effect transistor under load, the front is 110 ns, a small "ringing" is seen

Applying all the above calculations, the final scheme will look like this (Fig.7):

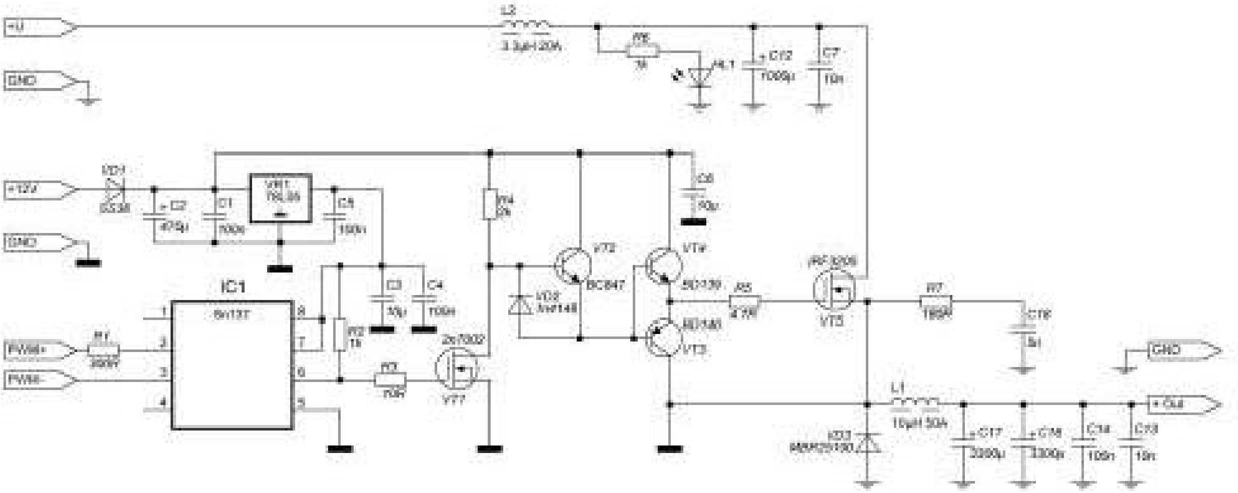

Figure 7 – The final schematic of buck converter

Conclusions

Was developed system for controlling the thermal evaporation of a metal in a vacuum to conduct research in the field of creating functional coatings. By the above calculations in the article, stable output parameters, low output noise, as well as smooth adjustment were achieved.

The advantages of the system include: compact design, high surrendered current, resistance to short circuit, low heating, the power supply from the power supply is taken less than just at PWM, due to the energy transformation at the inductor, as well as ease of control. The output voltage is constant, with pulsations less than 50 mV. The disadvantages include the noise that occurs when switching the field-effect transistor and the diode, the ways to minimize them were proposed and tested.

Thanks to the created in the result of the simulation and calculation of the control system in the form of a buck converter, research in the field of functional coatings described in [3,4] is possible.

REFERENCES

1. Steve Roberts DC/DC book of knowledge / Steve Roberts // RECOM Group Gmunden 2014. – 234 p.

2. Mattox Handbook of Physical Vapor Deposition (PVD) Processing: Film Formation, Adhesion, Surface Preparation and Contamination Control / Mattox, M. Donald // Westwood, N.J.: Noyes Publications, 1998 — 944p.

3. Mikhalev A.I. Modelirovaniye fraktalnykh struktur funktsionalnykh pokrytiy s uchetom skorosti napyleniya / Mikhalev A.I., Guda A.I., Zimoglyad A.Yu. Kovtun V.V. //Vísnik KHNTU -2018.- №3(66) S.- 115-120.

4. Zimoglyad A.Yu. Yssledovanye zavysymosty koeffytsyenta trenyya metallycheskykh plenok ot fraktalnoy razmernosty / Zimoglyad A.Yu., Guda A.Y., Kovtun V.V. Zhurba A.A. // Systemni tekhnolohiyi. Rehionalnyy mizhvuzivskyy zbirnyk naukovykh prats- 2018. - №2 (115) S.- 9 -13.

5. Horovits P. The Art of Electronics / P. Horowitz, W. Hill. - Moscow: Mir, 1995. – 154p.

6. Powell Vapor Deposition. The Electrochemical Society series / F. Carroll, H. Joseph, Oxley, J. M. Blocher // New York: Wiley, 1966— 158 p.