HARDWARE AND SOFTWARE MEANS FOR ELECTRONIC COMPONENTS AND SENSORS RESEARCH

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Abstract. The main results of RETwix development are presented in the paper. RETwix is an universal hardware and software means for laboratory research, which can be used for investigation both electronic components and arbitrary electrical, thermal, chemical or biochemical processes. Sensors, actuators and signal transducers of the Analog Front-End are used for this purpose. The RETwix means includes two CV-LAB devices (Capacitance & Voltage LABoratory) and UA-LAB (Universal Analog LABoratory). The peculiarities of construction and examples of RETwix using are described.

Keywords: embedded system, electronic components, sensor, laboratory research

SPRZĘT I OPROGRAMOWANIE DO BADAŃ ELEMENTÓW ELEKTRONICZNYCH I CZUJNIKÓW

Streszczenie. Główne wyniki opracowania RETwix zostały przedstawione w artykule. RETwix jest uniwersalnym sprzętem i oprogramowaniem do badań laboratoryjnych, które można wykorzystać do badania zarówno komponentów elektronicznych, jak i dowolnych procesów elektrycznych, termicznych, chemicznych lub biochemicznych. W tym celu zostały wykorzystane czujniki, aktuatory i przetworniki sygnału Analog Front-End. RETwix zawiera dwa urządzenia CV-LAB (Capacitance & Voltage LABoratory) oraz UA-LAB (Universal Analog LABoratory). Zostały opisane osobliwości budowy oraz przykłady zastosowania RETwix.

Słowa kluczowe: system wbudowany, elementy elektroniczne, czujnik, badania laboratoryjne

Introduction

Electronic information technology is currently one of the most dominant engines of modern society technological development. In addition to the traditionally electronic fields of technology – radio, telecommunications, information-measuring and computing, electronics and devices based on them have become important tools for the development of industry, biology, medicine, ecology, entertainment, etc [7–9]. The implementation of modern electronic devices in these industries is based on the concept of Embedded system [11]. Sensors, actuators, and signal transducers, called Analog Front-End (AFE), are the basis for the interaction of electronics with the physical world [10]. The relevance of the development and usage of Analog Front-End is due to the modern concept of the Internet of Things (IoT) [12]. Examples of IoT AFE are the Capacitive MEMS Accelerometer Analog Front-End for Ultra-Low-Power IoT Applications [1], Low-Power Low-Noise Inductorless Front-End for IoT Applications [19], Analog-to-Digital Acquisition Channel for an IoT Water Management Sensor Node [17].

The implementation of modern information technologies, including IoT, into various fields of science and technology requires intensification and further increase of education levels. The basis of education and science at all levels is experimental research. Modern publications on the development and implementation of hardware and software systems in training laboratories (Labs instrumentation for education) are connected with: e-Learning program [18], virtual hands-on Lab platform for computer science education [5], improving online higher education with virtual and remote Labs [15], virtual labs in engineering education [6], integrating remote labs in dotLRN [16], Internet of Things (IoT) remote labs for students education [13].

In accordance with the aforementioned problem, this paper presents the main results of the development of the RETwix – universal hardware and software tools for laboratory research, which solve the problems of educational and scientific laboratories of the broadest profile.

1. General characteristics of the RETwix

The elaborated RETwix includes two devices (Fig. 1) CV-LAB (Capacitance & Voltage LABoratory) and UA-LAB (Universal Analog LABoratory). The versatility of RETwix is that electronics components can be objects of research, as well as arbitrary electrical, thermal, chemical or biochemical processes. Measurements of the aforementioned processes are carried out with the help of the primary transducers or sensors – converters of the energy of investigated processes into an electrical signal. The shape and power of the primary transducer signal is, mainly, not optimal for the measurement process. Therefore, majority of the measuring devices use secondary (signal) transducers that amplify and normalize the signal. Considering the increasing demands on modern equipment, the importance of secondary transducers has increased significantly in the recent period. In some tasks, appropriate excitation is applied to obtain certain information about the investigated environment (process). Such excitations are formed by actuators.

Fig. 1. RETwix Devices

The RETwix provides the ability to perform laboratory tests in static and dynamic modes. In static mode, the measurement result is the monitoring of a certain value or DC (Direct Current) characteristics. For dynamic studies, a certain process is activated and the time dependencies of the parameters of this process are measured. Examples of dynamic objects of investigation are: charge and discharge of the capacitor; charge and discharge of chemical power sources; thermal relaxation; generation of charges in piezoelectric elements; chemical (biochemical) exo- and endothermic reactions.

The object of the investigation may be the RETwix itself. In the fields of measurement engineering, metrology and computer engineering, the investigation of the functionality and parameters of the complex allows to study the basics of information-measuring systems, digital-to-analog and digital-to-digital conversion, theory of measurement errors and more.

2. Signal transducers of capacitive sensors

The vast majority of signal transducers of modern capacitive sensors are based on two basic methods of measuring conversion. The first method is for SCM (Self Capacitance Measure) sensors, in which the capacitance C_X between the active sensor electrode and the interaction object that forms the passive electrode is an informative signal. In particular, it can be a person's finger or any other object with significant own capacity. It is obvious that in the process of measuring conversion, the change of potential or the measurement of current through a passive electrode is not possible. In terms of signal measurement, electrical interaction occurs only with the active electrode, and the passive electrode potential is considered quasi-constant or zero. The second method is for sensors of the MCM (Mutual Capacitance Measure) type, in which the informative signal of the measuring conversion is the mutual capacity between two active electrodes – transmitter (T_x – Transmit electrode) and receiver (R_x – Receive electrode). In such sensors, a voltage pulse is formed on the transmit electrode, which causes the charge of the measuring capacitor C_X to be induced, and the accumulated charge enters the measuring circuit through the receive electrode.

In modern capacitance sensors with microprocessor control, both conversion methods are implemented by two-stage switching of the measuring capacitor C_X. Consider the basic principles for implementing the circuit that perform the above-mention concepts, and the results of their model analysis.

Typically, sensors of the SCM type in the first phase charge the measuring capacitor C_X, and in the second – transfer this charge into the measuring circuit. Only the active electrode is used in both phases. The elementary signal circuit of such measurement is shown in Fig. 2a. In the first phase (Ph_1), the measuring capacitor C_X of the primary transducer is charged from the voltage source VS, and in the second (Ph_2), the charge obtained by the measuring capacitor $Q_X = C_X V_S$ is transmitted to the integrating capacitor C_{INT}. The voltage on this capacitor is the information signal of the transducer $V_{OUT} = V_{CINT}$. The charge of the C_X capacitor is carried out by the switch S_1, and the switch S_2 is used to transfer of the accumulated charge into the circuit of the integrating capacitor C_{INT}.
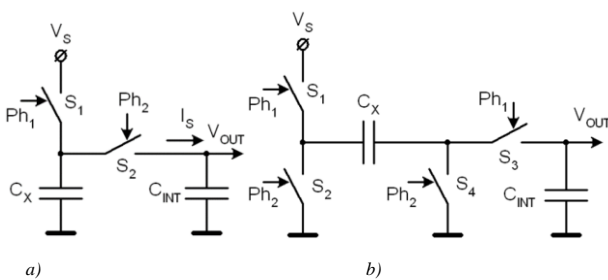

Fig. 2. The elementary signal circuit for capacitance measurement of SCM (a) and MCM (b) types

The elementary signal circuit that implements the principle of measuring conversion of MCM sensors is shown in Fig. 2b. The measurement conversion cycle contains the phase charge of the circuit of the sequentially connected measuring C_X and the integrating capacitor C_{INT} and the discharge phase of the measuring capacitor, during which the charge of the integrating capacitor remains unchanged. During the charge phase, the transmit electrode of the capacitor C_X is connected (switch S_1) to the positive voltage of the power source V_S, and the receive electrode to the integrating capacitor C_{INT} (switch S_3). Instead, in the discharge phase, the transmit and receive electrodes of the C_X

capacitor are connected to negative (zero) voltage (switches S_2, S_3) and the C_{INT} capacitor remains open.

In the vast majority of laboratory research tasks the capacitive sensors are used. Their informative quantity is the reciprocal capacitance between two active electrodes. Therefore, consider only the circuit of measuring transducer of sensors MCM type. The scheme of such transducer (Fig. 3) corresponds to the above-mentioned in Fig. 2b elementary signal circuit. The measuring transducer circuit contains an X_{OA} operational amplifier, the switches S_1, S_2, S_3, S_4 and the control signals sources VP_{11}, VP_{12}, VP_{21}, VP_{21} that control these switches.
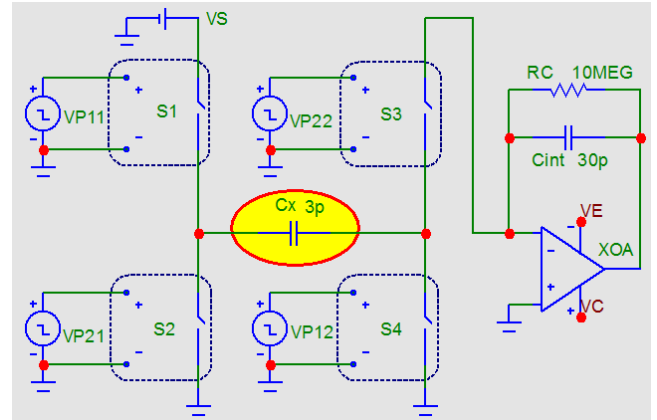

Fig. 3. Circuit of measuring transducer of MCM type

An integrated capacitor C_{INT} is connected into the negative feedback loop of the amplifier. Unlike the elementary circuit, such connection of the capacitor C_{INT} ensures high linearity of the transfer function. In parallel with the C_{INT}, a shunt resistor RC is switched on, which stabilizes the DC feedback circuit. In the first phase Ph1 of measurement transformation: VP_{11} = HIGH, VP_{12} = HIGH, VP_{21} = LOW, VP_{21} = LOW, where Low and HIGH are logical levels. At the logical level LOW switches are open (OFF) and at level High – closed (ON). Instead, in the second phase of Ph_2: VP_{11} = LOW, VP_{12} = LOW, VP_{21} = HIGH, VP_{21} = HIGH.

The result of a model study of the measurement transducer circuit in a Micro-Cap environment using SPICE models is shown in Fig. 4. Control signals, the voltages V [Ph_1] and V [Ph_2], are represented on the upper plot, and the output voltage V_{OUT} – on the lower plot.

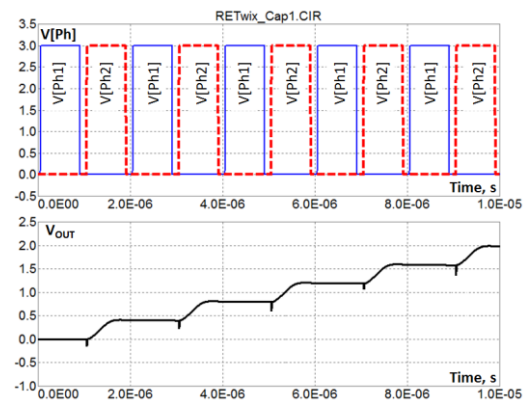*Fig. 4. Control signals V [Ph] and output voltage VOUT of the measuring transducer*

The output voltage is formed over several switching cycles (typically from 10 to 100), depending on the required speed and accuracy of the measurement conversion. Moreover, the higher speed, the lower accuracy, and vice versa. The diagrams depict 5 measurement conversion cycles.

It can be seen that in each of these cycles, there are three processes – voltage rise, voltage is kept at the constant level and spurious transitions. These spurious transitions are caused by transfer processes of switching and they are the subject for further optimization of the switching modes and output signal filtering.

The informative value of the measured capacitance is the increase in output voltage V_{OUT}, which is equal to approximately 0.4 V in each cycle.

3. CV-LAB device

The CV-LAB (Capacitance & Voltage LABoratory) device (Fig. 5) is designed to implement a wide range of capacitive sensors and created on their base integrated sensors of physical quantities.

Fig. 5. CV-LAB device

The CV-LAB includes (Fig. 6):
- MCM& MUX module – measuring transducer of MCM type sensors (Fig. 2) and analog multiplexer;
- AD7747 – module on high-precision $\Sigma\Delta$24-Bit Capacitance-to-Digital Converter and Voltage-to-Digital Converter;
- ATMEGA329P – microcontroller (the use of other microcontrollers or systems on crystal, including ESP32 with integrated Wi-Fi and Bluetooth radio standards is possible);
- Cross unit – digital line switching module, which, in particular, provides serial I2C / SPI communication interfaces to external modules – ADXRS453 (Digital Output Gyroscope), ADIS16334 (6 Degrees of Freedom Inertial Sensor), GY-80 (10 Degree of Freedom IMU board), etc.
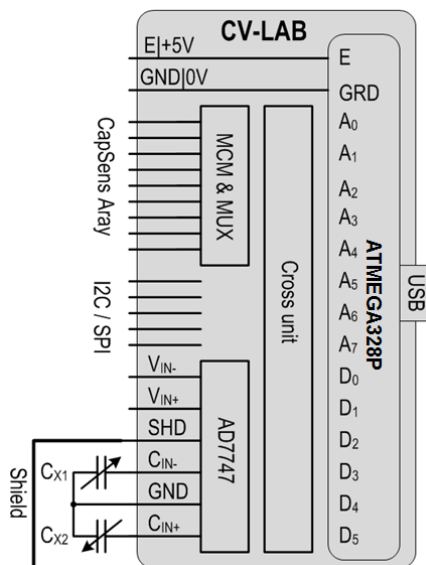

Fig. 6. CV-LAB scheme

The use of two modules for capacitance measurement is due to the specific of the tasks of wide profile capacitive sensors constructing. The part of the capacitive sensors, such as matrix touch panels or vibration sensors, require high speed conversion and multichannel. These parameters are provided by the MCM & MUX module with a rate of at least 3000 measurements per second. Instead, other capacitive sensors, such as biochemical or deformation sensors, require high resolution and accuracy of measurement transformations. These parameters are provided by a module based on the AD7747 Separator Converter, an electrical capacity measurement resolution is 10^{-16} F (the speed does not exceed 10 measurements per second).

In addition to the high-precision 24-bit capacity difference measurement (outputs – CIN1 (+), CIN1 (-)), the converter

provides also other important functions. Firstly, it is the active shielding of the input circuits (output – SHLD), which is extremely important during the measurement of very small capacitance changes. Such shielding is performed by auxiliary electrodes or shielding surfaces on which excitation pulses are formed. The amplitude of such impulses is adapted to the specific conditions of the investigated object. Secondly, the converter allows to synthesize auxiliary capacities, which, being included in the measurement circuit, allow to compensate the parasite capacities of this circuit. Such synthesis is performed by CAP DAC1, CAP DAC2 converters of "digital code – capacity" type. And thirdly, the converter allows to measure the difference of voltages at auxiliary leads VIN (+), VIN (-) with 24-bit resolution.

4. UA-LAB device

The UA-LAB (Universal Analog LABoratory) device (Fig. 7) is designed for laboratory researches with a wide range of functionalities. The UA-LAB hardware consists of digital module and analog front-end. The digital module implements the UA-LAB program management code, provides USB interface, analog-to-digital conversion, pulse-width modulation and some other features. Analog front-end units perform the functions of digital-to-analog conversion, amplification, and current-to-voltage conversion. The simplified functional diagram of UA-LAB is shown in Fig. 8. The following leads of the microcontroller are used: E and GND – supply voltage and ground, respectively; A_0, …, A_7 – analog inputs of eight-channel ADC; D_0, …, D_5 – digital outputs.

Fig. 7. UA-LAB device

Analog front-end units are implemented on OA_1, OA_2 AD8544 (CMOS Rail-to-Rail General-Purpose Amplifiers) operational amplifiers and R_{A1}, R_{A2} negative feedback resistors. The leads VIN1 +, VIN1-, VIN2 +, VIN2- are used to form the input circuits of the analog front-end. The output voltages of the V_{AMP1}, V_{AMP2} amplifiers are applied to the inputs A_6, A_7 ADC and form circuits $A_6|V_{AMP1}$ and $A_7|V_{AMP2}$, respectively.
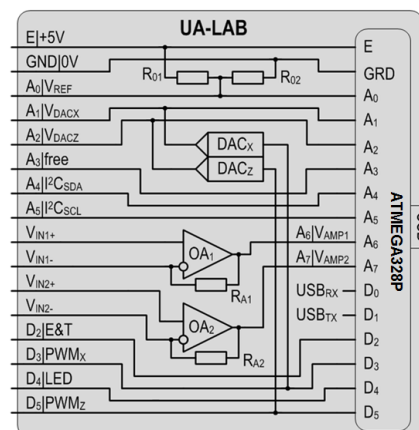

Fig. 8. UA-LAB scheme

The DAC_X and DAC_Z units provide the formation of two program-controlled analog voltages V_{DACX} and V_{DACZ}. The function of digital-to-analog conversion is implemented by the method of pulse-width modulation, followed by averaging using second order active filters. For simplification of the UA-LAB

scheme, the components of these filters, in particular operational amplifiers and corresponding RC circuits, are not given in Fig. 8. PWM_X and PWM_Z pulse width modulation control signals are generated at D_3 and D_5 digital outputs – D_3 | PWM_X and D_5| PWM_Z circuits, respectively. Measurements of the formed voltages V_{DACX} and V_{DACZ} are carried out using the inputs A_1 and A_2 ADC – A_1 | V_{DACX} and A_2 | V_{DACZ} circuits, respectively. A_3 ADC input is not connected with other circuits – A_3 | free. The A_4 and A_5 ADC inputs, can be used for voltage measurement and implementation the I^2C interface (SDA and SCL buses) with external modules – A_4|I^2C_{SDA} and A_5|I_2C_{SCL}.

The D_0 and D_1 digital outputs are used to implement signal circuits USB interface USB_{RX}, USB_{TX}. The digital output D_2 – circuit D_2 | E&T – is used to form the polarity of the voltages (E or 0) of the circuits under consideration when measuring current-voltage characteristics or time parameters of transition processes. As it was noted, digital outputs D_3 and D_5 optionally can be used for tasks requiring pulse-width modulation – D_3|PWM_X and D_5| PWM_Z circuit. The D4 digital output optionally can be used to control the light-emitting diode – D_4 | LED circuit.

5. Approbation

The approbation of the RETwix has been carried out in numerous laboratory research of microelectronic sensors based on resistive, capacitive, inductive, diode and transistor structures. The following modes are used in these tasks:
- formation of output voltages and their changes in accordance with the given algorithm of research;
- single measurement of one or more input voltages;
- measurements of the input voltage arrays in accordance with the output voltage change;
- multiple measurements of input voltages with activation of a certain process and selected delay between measurements.

There are three basic algorithms for informative signals generating:
- periodic eight-channel measurement for monitoring the investigated parameters;
- scanning eight-channel measurement, which determines the dependences of the studied parameters on the change (modulation) of the activating voltages;
- two-channel oscilloscope measurement with formation of arrays of the investigated parameters with fixed time parameters.

According to the basic parameters of the primary transducer the structures of capacitive sensors can be divided by the change of:
- the area of the inter-electrode overlap;
- the distance between electrodes;
- the parameters of the inter-electrode dielectric;
- the impact of environmental objects.

On the basis of these structures sensors of spatial displacement; pressure sensors and matrices; accelerometers; tactile matrices; humidity sensors; devices for chemical and biological research; electrode scanners; ultrasonic tomographs; condenser microphones; fingerprint scanners; non-contact control devices are realized.

An example of capacitance measuring by a sensor that demonstrates the ability to achieve resolution 10^{-16} F is shown in Fig. 9. In this example, a CV-LAB module based on a high-precision $\Sigma\Delta$ 24-Bit converter AD7747 is used. In accordance with current trends in the development of sensor electronics, the use of RETwix has significant relevance in the concept of Data fusion and Sensor fusion[14]. In this concept, we have implemented integrated devices for combining thermal measurement methods with capacitive [2], magnetic [4] and optical [3] sensors. Such integrated devices are the basis of IoT sensors for chemical and biological analysis in the concept of Lab-on-Chip.
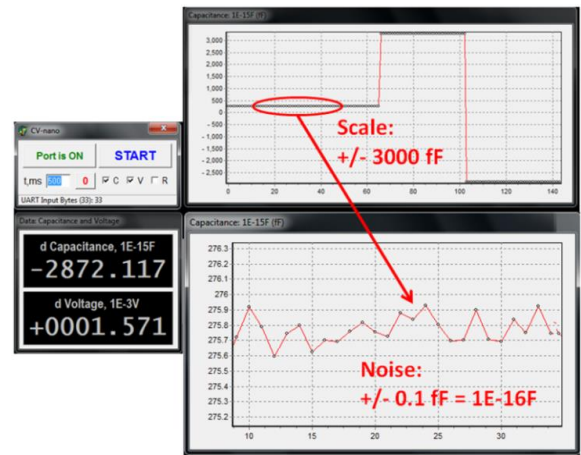

Fig. 9. Example of capacitance measuring by a sensor based on AD774 converter

Analog front-end configuration and measurement results of the UA-LAB are presented in the following examples:
- Fig. 10 – measurement of current-voltage characteristics of the transistor structure T_X;
- Fig. 11 – implementation of sensors based on primary transdusers of the bridge type R_B;
- Fig. 12 – implementation of sensors based on differential optocouples LED – D_{PH1}, D_{PH1};
- Fig. 13 – implementation of an integrated device based on the coil L of magnetic field forming and Hall sensor HG for its measurement;
- Fig. 14 – the result of the scanning measurement of the current-voltage characteristics of the transistor structure;
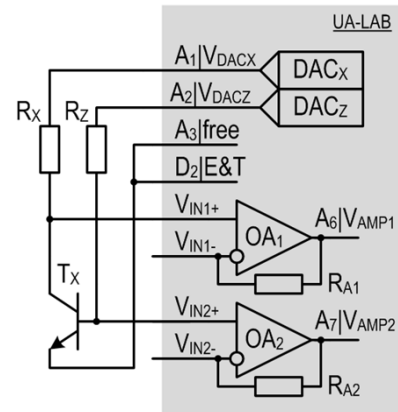- Fig. 15 is the result of a two-channel oscilloscope measurement of transients in an RC circle.

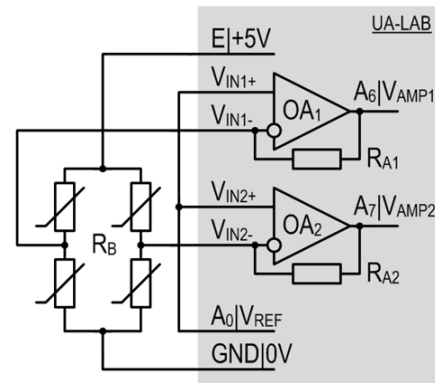Fig. 10. Analog front-end of the transistor structure

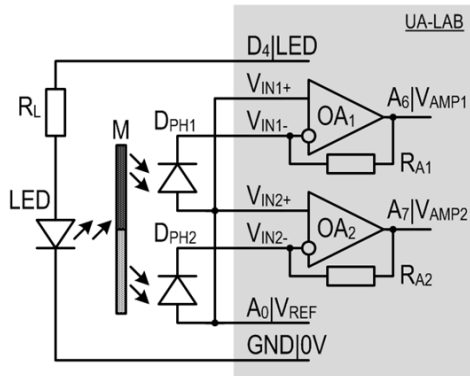Fig. 11. Analog front-end of the bridge type sensor

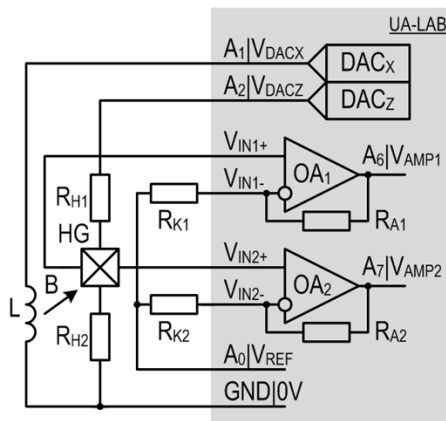*Fig. 12. Analog front-end of the differential optocoupler*

Fig. 13. Analog front-end of magnetic field formation and measurement
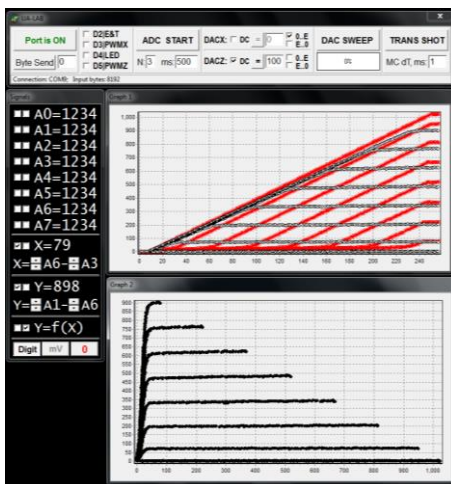

Fig. 14. The result of the scanning measurement of the current-voltage characteristics of the transistor structure
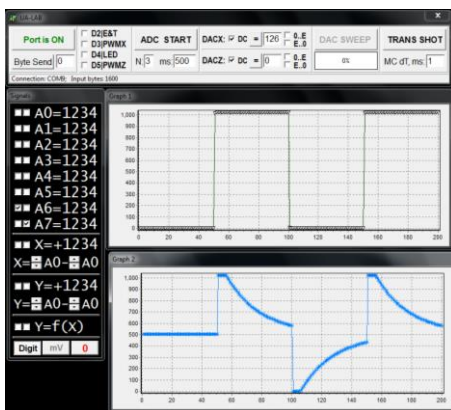

Fig. 15. The result of two-channel oscilloscope measurement of transition processes in the RC circuit

In accordance with current trends in the development of sensor electronics, the use of RETwix has significant relevance in the concept of Data fusion and Sensor fusion [13]. In this concept, we have implemented integrated devices for combining thermal measurement methods with capacitive [14], magnetic [15] and optical [16] sensors. Such integrated devices are the basis of IoT sensors for chemical and biological analysis in the concept of Lab-on-Chip

6. Conclusions

The main results of development and examples of using the RETwix hardware and software for laboratory research are presented. RETwix includes two devices – CV-LAB (Capacitance & Voltage LABoratory) and UA-LAB (Universal Analog LABoratory).

The principles of measuring conversion in capacitive sensors of two types SCM – Self Capacitance Measure and MCM – Mutual Capacitance Measure are analyzed. An informative signal for the conversion of SCM type sensors is the capacitance C_X between the active electrode of the sensor and the object which is the passive electrode. In particular, it can be a person's finger or any third-party object with significant own capacity. An informative signal for the conversion of MCM type sensors is the mutual capacity between two active electrodes, a transmitter (Tx – Transmit electrode) and a receiver (Rx – Receive electrode). In such sensors, a voltage pulse is formed on the transmit electrode, which causes the charge of the measuring capacitor CX, and the accumulated charge comes to the measuring circuit through the receive electrode.

The main modules of the CV-LAB are the MCM (MCM & MUX) type measuring transducer and the high-precision $\Sigma\Delta$ 24-Bit Capacitance-to-Digital and Voltage-to-Digital Converter AD7747. The UA-LAB includes digital and analog modules. The digital module implements the control code, provides USB interface, analog-to-digital conversion, pulse-width modulation, etc.

In accordance with current trends in the development of sensor electronics, the use of RETwix has significant relevance in the concept of data fusion and sensor fusion (Sensor fusion). In this concept, we have implemented integrated devices for combining thermal measurement methods with capacitive, magnetic and optical sensors

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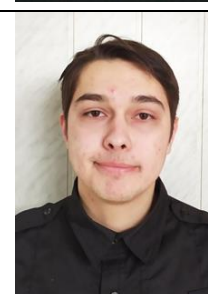
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