

Computer Controlled System for the Magnetron Sputtering Deposition of the Metallic Multilayers

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Abstract—Deposition of the metallic multilayers is a part of the scientific program on the chemical reaction leading to intermetallic compound formation. This reaction is known as self propagation high temperature synthesis (SHS). The key problem in this investigation is to produce the metallic multilayer system with good repeatability of thin films thicknesses. Thin should be thin, parallel and with low volume of intermixing region between components. Computer control system for the pulsed (mid frequency MF) magnetron sputtering equipment dedicated for metallic multilayers deposition is presented in this paper. The rotation velocity of the sample holder and the gas inlet through membrane valves are the main parameters controlled by the system. Parameters of the magnetron gun power supply, sample temperature and technological gas pressure are registered. The process cards which define all process parameters are collected for each dedicated process type. All cards are collected in a process cards library which permits for full automatization of all operations. Software was written in a graphical LabVIEW environment.

Keywords—process control system, Al/Ni, magnetron sputtering

I. INTRODUCTION

THE intermetallics and their compounds with nitrogen, carbon, silicon or boron are strongly investigated due to their properties and possible application. Some of them are superconducting, others have high temperature melting point and good mechanical properties in high temperatures. There are some intermetallics with high corrosion resistance or with shape memory effect. It is a group of the new materials generation for different sophisticated applications. Intermetallics could be prepared in a few different way. One of the method is self-propagation high-temperature synthesis (SHS). SHS is realized as an exothermic reaction in adiabatic system. This process has a solid state (or liquid) burning character. Initialization of the reaction could be obtained due to local (e.g. laser) or total heating of the components. Reaction bed is mainly the mixture of micropowders. In the proper conditions, as a result of exothermic reaction thermal wave is created and propagated with velocity up to 20cm/s. Temperature is rising very fast up to 1500°C/s. These reaction parameters make the investigation of its kinetic difficult. Also creation of the defined intermetallic compound is still not clear. To make the observation of the reaction easier the thin film multilayer system consists of two metals is proposed as investigation system. The well defined thin films can be observed by means

of transmission electron microscopy. First papers on SHS [1-7] were published at the end of eighties last century. The idea to substitute the micropowder mixture by multilayer system especially in NiAl intermetallic compound was started last ten years [8-11]. The multilayer system should be precisely characterized. It means the thickness has to be the same and interface mixing zone should be as narrow as possible. That creates a good conditions for the investigation of the synthesis reaction the full automatization of the deposition process is required. The scientific program includes investigation of the multilayer of NiAl, TiAl and NiTi. Three metal targets Ti, Ni and Al are prepared for deposition processes. Sputter yield for each material is different. So as a first step it should be measured. To get repeatable thicknesses in multilayer system the stability of the power supply of the magnetron gun and argon pressure in the chamber should be stable. The most important is to find such deposition parameters for which the intermixing region between films is as small as possible. The intermixed region aggravates heat transport in the reaction zone [8] and decreases its velocity [10]. The similar effects one can observe in case of dissolution of the reaction bed by the products of the reaction.[5,7]. The investigation of the intermetallic compound creation requires precise deposition of thin films with defined thicknesses and sequences.

II. DESCRIPTION OF EQUIPMENT AND SPUTTERING PROCESS

Main component of the sputtering equipment is a vacuum chamber with the volume about 50dm³ with pumping system consists of the diffusion and the rotary pumps. Pumping speed is regulated by a special construction of the valve gate mounted on the diffusion pump. Two cylindrical magnetron guns with metallic target of 50 mm in diameter are mounted in vacuum chamber. Final pressure of the chamber is 10⁻³ Pa. The pressure is measured by vacuum gauge type Inficon PSG550. The vacuum chamber has a water coat between chamber wall for heating (during pre-pumping) and cooling (during deposition) [12]. Substrates for layer deposition are mounted in a rotating sample holder which is rotated with two dedicated for each magnetron speeds.

The chamber is supplied by working gas, in this case argon (Ar) through two membrane valves controlled by square signals generators. The temperature of the substrate is measured by a thermocouple. Three windows in the chamber wall are used for optical inspection of the deposition process. General overview of the system is presented in Fig. 1. Two metallic targets (Ni and Al) are installed in the magnetron guns.

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Fig. 1. General overview of the multilayers sputtering equipment

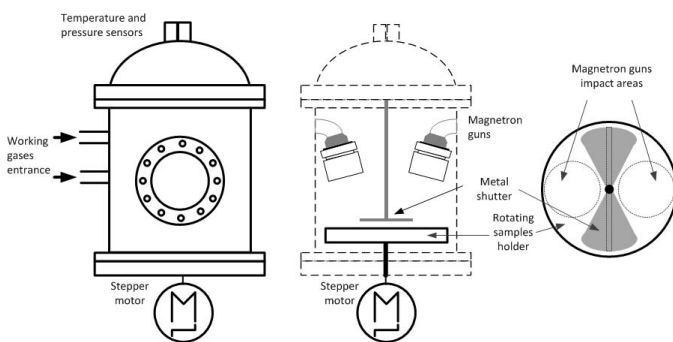


Fig. 2. Main parts of the sputtering equipment

Discharge spaces of the each magnetron guns are mechanically separated. The samples are transported from first half to the second one by rotating sample holder which is driven by stepper motor. Angular velocity in each half are set up in a computer control program. For registration other process parameters, temperature and pressure sensors are installed in the chamber. The design of the vacuum equipment is presented in Fig. 2. After the substrate are mounted in substrate holder the vacuum chamber is closed and pumped down to the pressure 10^{-3} Pa. Later on the argon gas is leted in to the chamber up to the dedicated process pressure. Next step it is switching on the magnetron guns and the stabilization of discharge parameters. The same time the substrates are situated under the shutter to prevent some oxide or dust deposition. The stabilization of the magnetron guns working parameters is controlled by rising a substrate temperature. The curve showing the rising temperature is presented in Fig. 3.

As a next step, rotation of the sample holder is started and the substrates are transported through the discharge zone (circle marked region in Fig. 2). The operator could set up the rotation velocity in each half of the turn and the number of rotations. All parameters included gas pressure and substrate temperature are stored in data sheet for current process. The cross section of the multilayer system is shown in Fig. 4. To fulfill all requirements for each process the library of process

cards is prepared. One can choose a desired process from this library for the specific targets.

III. CONTROL SYSTEM

In order to prepare reproducible multilayer structures with defined thickness, dedicated control system was built (in the LabVIEW graphical environment) [13, 14]. The control system has a modular structure, each end device is controlled directly using a dedicated, single-chip microcontroller module. The principal element of the system is the control software installed on PC computer. All control modules are controlled by this main application. It performs parameter setting for the sputtering process. The communication between the main computer and the modules is wireless. It uses transmitters operating in accordance with the ZigBee protocol. This increases the flexibility of the system. If you need to connect a new module to the system, only the implementation of the wireless communication transmitter is necessary. Then of course the main program should be modified (by support for a new control module). The rest of the system remains unchanged.

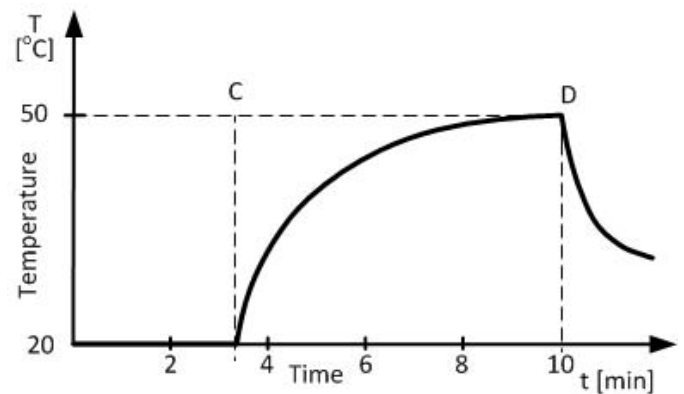


Fig. 3. Temperature versus time characteristic of the deposition process

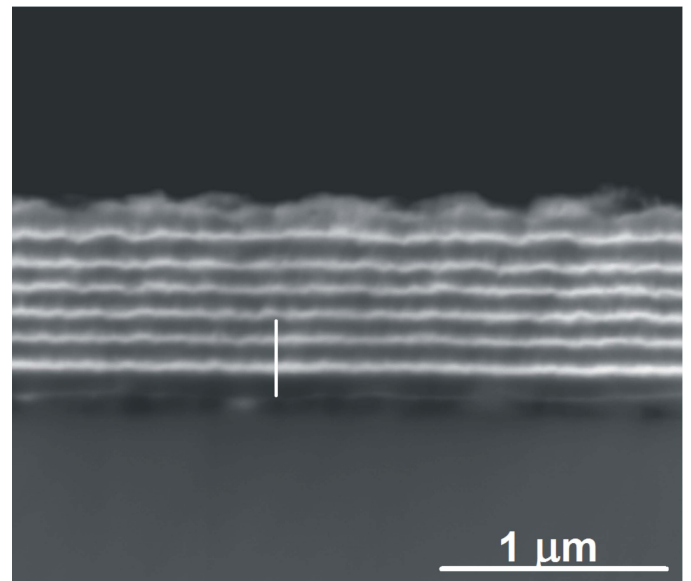


Fig. 4. Cross-section SEM micrograph of Ni/Al multilayers film. Dark and light layers correspond to Al and Ni films respectively

Main application sends the control process parameters to actuators. When parameters are sent and accepted, sputtering process starts. Some parameters can be changed during the process, others only after its completion. During the deposition process control modules read information about temperature and pressure of the working gas and periodically send it to the central computer. The data are archived in a file documenting the process.

A. Wireless Communication Protocols (ZigBee)

ZigBee protocol [15-18] belongs to a family of LR-WPAN protocols (Low-Rate Wireless Personal Area Network), which are characterized by the low bit rate and transmission range of no more than 100m. ZigBee standard defines a recommendation for the creation of the network layer and the user application. The process of data transmission is carried out according to the IEEE802.15.4 standard [16]. Because ZigBee network always performs transmission of data in accordance with these recommendations, the two standards are considered together, treating them as a single unit.

1) *IEEE 802.15.4 standard*: Standard describes the parameters of the Physical Layer and the MAC (Medium Access Control) sublayer, which manages access to the transmission medium. The main features of the standard are for example [16]:

- transmission of data with the speed equal: 20, 40, 100, or 250 kb/s,
- the ability to work in a star or a peer-to-peer topology,
- two addressing modes - short with 16-bits or extended with 64-bits address length,
- the ability to provide the Quality of Services (QoS) through the mechanism of guaranteed time-slots (GTS) Multiple Access protocol to link, detection of the carrier and collision avoidance CSMA/CA (Carrier Sense Multiple Access with Collision Avoidance)
- low power consumption,
- the possibility of monitoring the energy level in the transmission channel,
- a straightforward call quality evaluation LQI (Link Quality Indication).

A fundamental element of the network structure is a device that can be implemented as:

- Full-Function Device (FFD)
- Reduced-Function Device (RFD).

Two (or more) of the devices located in the user's personal space, which are communicating with each other using the same physical channel form a WPAN. Such a network must include at least one FFD-type device that works as a coordinator of the network. The developed system uses the star topology (Fig. 5). In a such network direct dialogue is possible only between the coordinator and the other network nodes. For networks operating in this configuration, the central node is usually powered from the mains, while the remaining nodes can be battery-operated.

2) *ZigBee standard*: Recommendations for ZigBee protocol have been developed by the ZigBee Alliance, a consortium of over 150 companies from around the world. The network

layer defines recommendations for cooperation with the MAC sublayer and the interface to the application layer. The main tasks of the layers are [17]:

- network data unit generation,
- messages routing,
- ensuring transmission security,
- attaching and detaching of the devices
- configuration of new devices,
- creating a new network,
- support for the addresses allocation,
- identification of the neighboring nodes,
- route recognition,
- receiver management (switching between active and inactive states).

In the application layer three functional sub-layers have been defined :

- Application Support Sublayer,
- ZigBee Device Object (ZDO),
- the structure of the application.

ZigBee application layer defines the environment in which the device stores application objects. These objects are identified by the endpoint address (it is possible to define up to 240 different application objects for a single device). In each of the devices two special endpoints are defined: the address '0' is reserved for communication with the ZDO object and '255' point, reserved for the broadcast addressing mode. Additionally the "profile" parameter is defined for application layer. It describes the principle of operation of the device and specifies the message format that are dedicated for the purpose of controlling processes associated with the profile. An example of an application profile can be a home automation system profile, which defines the main format, content of the message and the operation of applications designed for such use. The device can support multiple profiles. ZigBee object represents the basic functionality class, which provides an interface between the application object, device profile and application support sublayer. ZDO is responsible for:

- initialization of the application support sublayer, network layer, and services related to security of the transmission,
- collection of the configuration information (from the endpoints), which are used for recognition and implementation of the identification services, network management
- and security mechanisms.

ZigBee object communicates with the lower part of the stack by the end point with address '0'. The hardware detection process allows for mutual identification of network nodes. The process of services identification allows to identify properties of the one device by another. This mechanism is possible through the use of descriptors that describe the network nodes. Recognition of services can be realized in two ways: by sending a request to the descriptors for a particular device or by broadcast sending a set of descriptors and waiting for a response from the devices that match the transmitted information.

TABLE I
 INITIALIZATION COMMANDS FOR THE COORDINATOR MODULE

AT Command	Description
ATV0	Set the answer format into numerical form
ATX0	Set a transmitter to send EVENT and DATA to a host
AT+GSN=1	Set extended address value for the node equal to 1
AT+WROLE=0	Set router role
AT+WSRC=00	Set the short address value equal to 0
AT+WPANID=1500	Set node's extended PAN ID
AT+WCHMASK=100000	Set node's channel mask (this one enables channel 0x14 only)
AT+WJOIN	Perform network join

 TABLE II
 INITIALIZATION COMMANDS FOR THE END MODULES

AT Command	Description
ATV0	Set the answer format into numerical form
ATX0	Set a transmitter to send EVENT and DATA to a host
AT+GSN=3	Set extended address value for the node equal to 3
AT+WROLE=2	Set end device role
AT+WSRC=11	Set the short address value equal to 11
AT+WPANID=1500	Set node's extended PAN ID
AT+WCHMASK=100000	Set node's channel mask
AT+WJOIN	Perform network join

B. Control System Architecture

The structure of the communication system is shown in Fig. 6. The main module of ZigBee network (system coordinator) is connected to the PC computer. It is controlled directly from the central application via the USB interface. Each of the end devices has its own ZigBee receiver with a unique address, so that the communication between the central system and the executive points is realized as point-to-point transmission. Additionally it is independent of the state of the rest of the system. It is also possible to transmit information in the broadcast mode. This type of transmissions is used, in the developed system, to obtain the time synchronization between the devices. Of course, a full synchronization in such a system can't be achieved. In order to ensure the highest level of time synchronization, the systems should have a common control unit, otherwise it will always appear some time discrepancies in the system (this is distributed system) [19-23]. When the main application is started, the software module that controls operation of the ZigBee coordinator is initiated. ZigBee network management software is primarily responsible for system initialization, creates a new network and sends and receives messages from the control devices. The computer communicates with ZigBee device using a set of AT commands, through the USB interface. Messages received by the ZigBee module can be categorized into three groups:

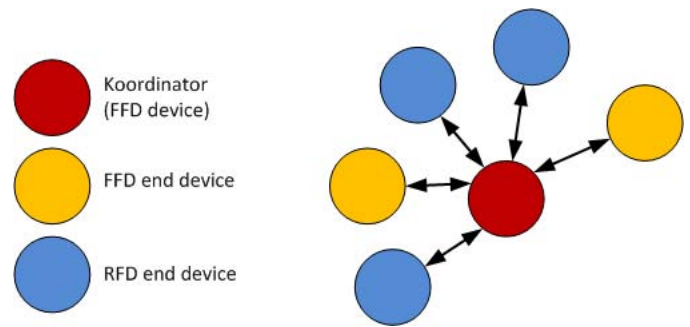


Fig. 5. Star topology of the sensor net structure

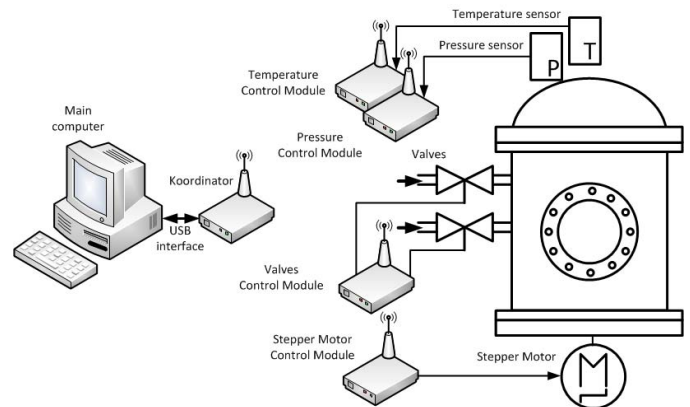


Fig. 6. Control system architecture

- Messages with the status of the currently realized action - in this case, the ZigBee module sends one of the two codes: code 0 - if the operation is finished properly or code 4 if not.
- Data received from the network - in this case, the ZigBee transmits first code indicating the data is received, then the device address from which the message was received, the length of the data fields and "user's" data.
- Information about the event - in this case, the ZigBee transmits a special code indicating the occurrence of an event and its identifier. The event may be, for example, a disconnection from the network one of the control devices. This information can be used as a security alarm, after which the software can stop the deposition (only in well-functioning system the process is carried out).

Initialization of the coordinator module is implemented using a set of special commands (AT Hayes orders) sent to the device via the serial interface. Table 1 shows the currently used commands for ZigBee module initialization, with a brief description. These commands are sent to the device whenever the software is started [23]. The program controlling the operation of each of the steering equipment (end devices) is divided into two parts, one of which is responsible for process control of the sensor or actuator and the second one controls ZigBee module. Tasks of the ZigBee module installed in the end device are practically the same as for the module implemented in the network coordinator. The difference between these two modules is only in a few initialization commands. Table 2 shows the commands used

to initialize a ZigBee module in the end devices with a brief description. These commands are sent to the ZigBee module when the power is turned on. It is necessary to perform before a start-up procedure of the network coordinator (the equipment can only join an existing network that was previously created by the coordinator) [23].

1) *Stepper motor control module*: Stepper motor controller module has been developed based on single-chip microcontroller ATMEGA8L. Block diagram of the device is shown in the Fig. 7. Microcontroller application performs two functions:

- support for ZigBee wireless communication module (receives requests, sends confirmations, sends alarms)
- generation of steering pulses for stepper motor.

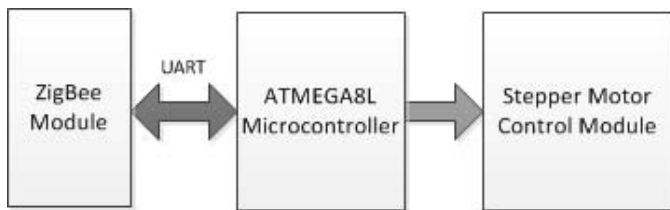


Fig. 7. Block diagram of the step motor controller

After powering microcontroller initiates the ZigBee communication module, then connects to the network organized by the system coordinator. In the case of switching on the device before start of the main application, the problems to join the network occurs. So the initialization procedure is repeated until the confirmation of a positive coordinator detection and join the network (it is impossible to start the engine if there is no active connection to the main control application). When the device is just connected to the ZigBee network, it waits to receive from a central computer, parameters of the engine work (rotation time given in minutes). After message receiving the microcontroller converts the data determining the delay time between motor-control pulses. This procedure is performed in the device, not in the central system, because for thus it is possible to become independent central application on the engine and the control module type. These elements can be changed without imply changes in the application itself.

When the motor control parameters are already calculated, the microcontroller sends to the central system message with confirmation of receiving the correct operating parameters and willingness to take off the process. It then goes into receive mode, and is waiting to receive the message 'START PROCESS' or request 'change operating parameters'. When the process is running the microcontroller in parallel realizes the stepper motor control algorithm and system messages listening.

Since the start of the process, until the end the controller does not respond to any system messages beyond the 'STOP' command. If it receives such a command, the motor is stopped, microcontroller sends information about the early completion of the process to the main system and changes the state into the standby mode (it is waiting for the message which contain new parameters of the work). If, during the sputtering process microcontroller does not receive the interrupt message, the

process will be ended in a predetermined time and the 'PROCESS FINISHED' message is sent into the central system. Rotating holder which realizes sample displacement in the magnetron sputtering gun area, is driven by a stepping motor connected to the drive shaft by multiple gears. As a result, relatively heavy rotation element may be moved with the low-voltage, bipolar stepper motor (9V) controlled by the pulse waveform.

There exist lots of stepper motor control algorithms. The most commonly used are [24-27]:

- Single-Coil Excitation - only one coil is energized each time. This method is rarely used, generally when power saving is necessary. It provides less than half of the nominal torque of the motor, therefore the motor load cannot be high.
- Full step drive - the coils are energized in pairs. According to the connection of the coils (series or parallel) the motor will require double the voltage or double the current to operate that needs when driving with Single-Coil Excitation. It is possible to obtain twice higher torque of the motor (the nominal torque of the motor).
- Half stepping - all coil pairs can be energized in the same time, causing the rotor to rotate half the way as for a normal step. This method can be single-coil or two-coil excitation as well. This method has a particular advantage in relation to previous methods, it decreases the effect of the mechanical resonance engine.
- Microstepping - this is the most common method to control stepper motors nowadays. The idea of microstepping, is to power the coils of the motor not with pulses, but with a waveform similar to a sin waveform. This way, the movement is more smoother, making the stepper motor suitable to be used for high accuracy applications. With microstepping, a stepper motor can rotate almost continuous, like simple DC motors. The method suppresses very well the mechanical resonance effect and reduces the amount of energy needed to make a single step.

In the developed system bipolar stepper motor is controlled with the implemented in microcontroller microstepping method. Four transistors forming the bridge (known as H-bridges - Fig. 8) are used for motor driving. Construction of the bridge provides protection for the motor coils during switching by using a dedicated MOSFET transistor with additional protection diode in the structure (IRF540). FETs are driven by bipolar transistors, which protect the system against short-circuit at a time when there is not any signal on the input. Additional bootstrap circuit (diode and capacitor) guarantees proper polarization of the transistor gate with voltage higher than the supply voltage. It ensuring its full opening and reducing heat loss.

2) *Electro-valves control module*: Electro-valves control system monitors the amount of working gas in the sputtering system. Based on the parameters sent from a central system (via the ZigBee), the microcontroller creates two independent PWM (Pulse Width Modulation) signals which controls power supply of the valves (Fig. 9).

Two switching systems, built with unipolar transistors, work completely independently, allowing the dispensing of

two different types of working gas. After programming the communication interface, the device waits for the command actuating sputtering process and starts generation of signals which control the valves. It is possible to reprogram the parameters of the work during the process. If the sputtering process is under way, and the unit receives from a central computer command 'NEW PARAMETERS', it changes the frequency and filling factor of the PWM signals. System is reprogrammed and valves are controlled by the new signals. The central application shall be notified of this fact by the special confirmation message.

3) *Pressure and temperature sensors control modules:*

Both, used in the sputtering system, sensors are controlled in the same way. After receiving from the microcontroller (via the UART interface) 'READ DATA' command, send back the value of the measured parameter. Of course, the data format and bit resolution are different but the form of control and communication with the central system are identical.

First, microcontroller initiates the ZigBee modules and performs connection to the network. Then the module changes the state into idle mode and is waiting for the operating parameters. In this case, the frequency of reading (and transferring) data from the sensors, is the adjustable parameter. After programming, the device is waiting for the command to start the process and then starts periodically send data to the coordi-

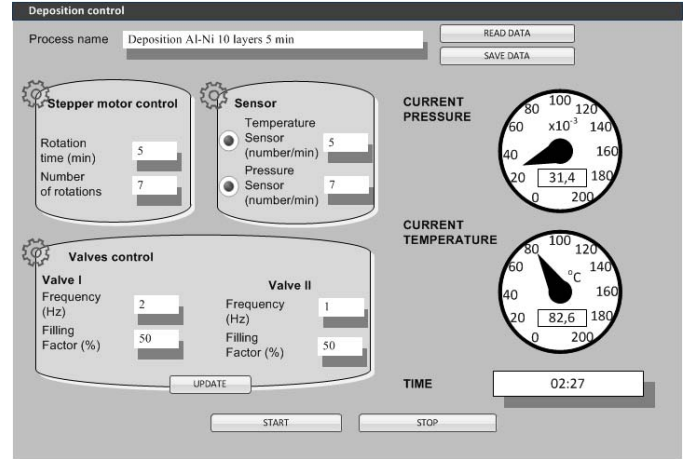


Fig. 10. Operator's interface with current parameters

nator. 'END PROCESS' command finishes the transmissions. Because both devices are working almost in the same way and are sending data to the coordinator with the same time interval, an additional mechanism for differentiating the starting time is implemented (to avoid collisions in the system). In addition to information on the frequency of transmission, module receives information about the interval of postponing of the transmission moment. For example, if the delay for the temperature module is '0' and the pressure module '1', the temperature information is transmitted instantly, and the pressure after the 100ms delay.

C. *The Main Application*

The system is controlled by a computer application, working on a PC computer with Windows operating system. It permits parameters setting for the sputtering process which control motor and valves work and reads the temperature and pressure from sensors. Example application screen shot is presented in Fig. 9. The sputtering process is carried in few steps. The number of steps depends on the number of layers which are to be sprayed on the sample. The residence time of the sample in the magnetron beam determines the layer thickness.

This time is controlled by the stepper motor speed. During a single rotation, two layers are sputtered (one by each magnetron). In the control application it is possible to determine the time of the single rotation and the number of full rotations of the substrate. After determining these two parameters and transfer them to control devices, start of the sputtering process is possible. (START button in the application). From this moment is not possible to reprogram the engine control unit, with no early termination of an ongoing process. Working gas pressure is controlled by two electro-valves. In the main application the frequency and filling factor for steering signal is set (decisive for the opening time of the valve). After entering the parameters for the controllers the sputtering process is started. Application can sent to the controller new adjustable parameters (the 'UPDATE' button). It does not interfere in any way in the process of deposition, which is still continuing. This fact is noted only in a backup file, which is stored

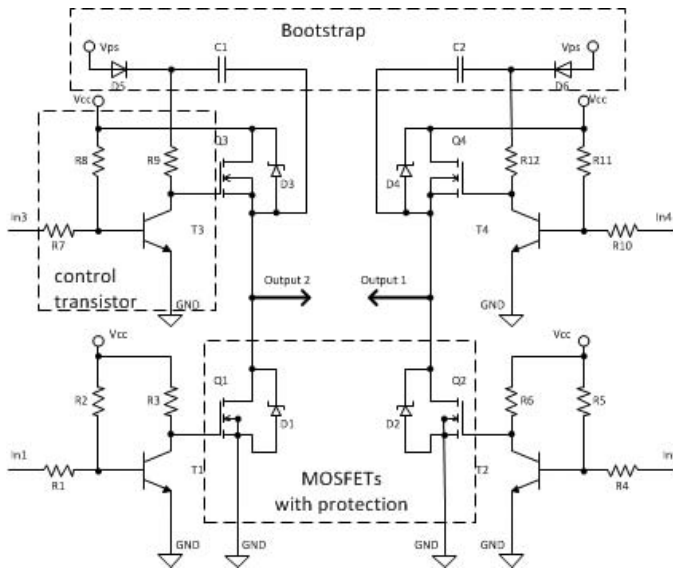


Fig. 8. H bridge diagram

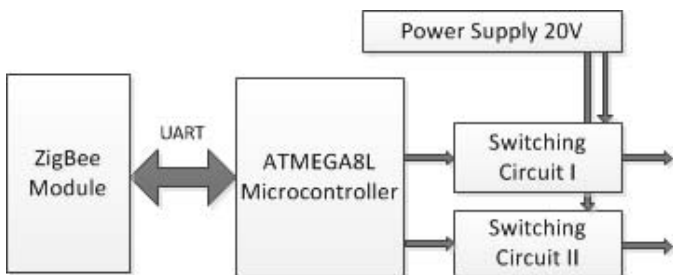


Fig. 9. Block diagram of the electro-valves controller

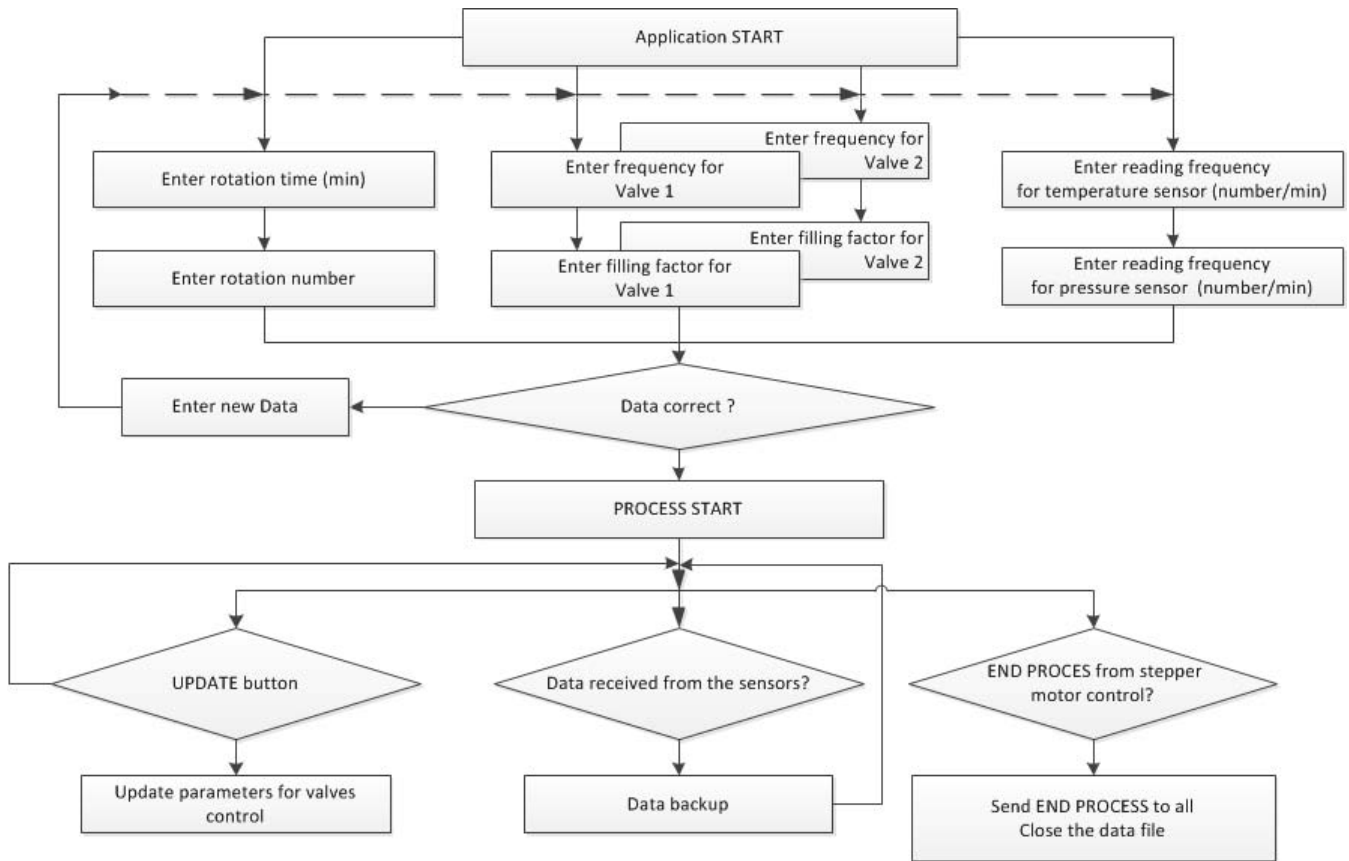


Fig. 11. Algorithm of the application

information about changing the process parameters, the new values and time of the event. The readout of temperature and pressure is initiated by the main control applications, but later runs independently. If the service is activated, it is necessary to define the frequency of sensor reading (for each sensor independently). This value is given in an number of readings per minute, and because of the security of transmission can't be greater than 10. It shall be sent to the controller at the start of the deposition process. Controller automatically transmits readings (with the programmed frequency) to a central system. Application offers possibility of backup information about realization of the sputtering process. When the process is started, the application creates a text file, in which (in the header) all parameters of the work are stored, and then, for the entire duration of the process temperature and pressure values sent from the sensor (and the time in which they were read). The algorithm of main operation is illustrated in Fig. 11. The application also implements the functionality bookmarks process. After entering all the parameters controlling devices in the system, they can be saved to a so-called *Process tab*- file with information about the parameters of the process (text file with the extension .vps). If the tabs are created, it is possible to load all the adjustable parameters of the process via the button LOAD DATA TAB. All fields of application are then filled in automatically. In this way it becomes possible to create a library of specific processes that can easily be repeated.

IV. CONCLUSION

Vacuum equipment for the pulse magnetron sputtering deposition of the metallic multilayers was designed and constructed. The dedicated software for process control was written and tested. The modular architecture of the software is easy to modify and it permits to add new modules for extra task (e.g. controlling for extra sensors). Wireless communications between main applications and executable modules eliminates cables connections and makes easier applications of extra modules. The modular architecture has also main application. The graphical environment LabVIEW makes easy any development of new functions or functional modules. All process parameters and functions are fully controlled by the dedicated software. Very good repeatability of the metallic multilayers thickness and structure is obtained.

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