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AUTOMATION OF NANOPARTICLE SYNTHESIS PROCESSES IN A PLASMA ENVIRONMENT USING LABVIEW

Abstract

This work presents an automated control system for the synthesis of nanomaterials by plasma-enhanced chemical vapor deposition (PECVD), implemented using the LabVIEW software environment. The main objective of the study is to develop an integrated hardware-software platform that enables sequential control of the key stages of the PECVD process, including vacuum chamber preparation, pressure monitoring, working gas supply, plasma ignition, power matching, cyclic nanomaterial growth, and optical monitoring of nanoparticles in the plasma environment. The use of LabVIEW made it possible to integrate actuator control, experimental parameter acquisition, and real-time process visualization within a single automated system. The automated cycle begins with evacuation of the reaction chamber to a predefined base pressure. Transition to the next stage is permitted only after the specified pressure threshold has been reached, ensuring reproducible initial conditions for each experiment. The program then controls the supply of the working gas through mass flow controllers (MFCs). In this work, two gas-flow control modes were considered: analog control using a 0÷5 V voltage signal and digital communication via RS-232 interface. It was shown that the analog approach requires accurate scaling of the control voltage, since applying 5 V corresponds to full-scale opening of the controller and results in the maximum gas flow. In contrast, the RS-232 interface enables the gas flow rate to be specified directly in sccm, improving the accuracy, flexibility, and convenience of gas-environment control. After pressure stabilization, LabVIEW initiates RF plasma ignition and executes the RF matching algorithm aimed at minimizing reflected power and improving the stability of the plasma process. A separate software module implements the cyclic nanomaterial growth mode, in which the plasma-on time, plasma duration, and total number of synthesis cycles are predefined. This approach makes it possible to control material accumulation on the substrate and to correlate the process parameters with the morphological characteristics of the resulting nanostructures. The final module of the system is designed for optical monitoring of the nanoparticle cloud density in dusty plasma. For this purpose, the change in the intensity of laser radiation passing through the plasma region is recorded using a photodetector and a Keithley 2401 measuring unit connected to LabVIEW via RS-232 interface. The difference between the initial and modified optical signal intensity is used as a diagnostic parameter characterizing the formation and temporal evolution of nanoparticles. The developed system demonstrates that LabVIEW can be effectively applied not only for the automation of individual instruments, but also for the implementation of a complete digital control cycle for PECVD-based nanomaterial synthesis.

Keywords: PECVD, automated plasma synthesis, nanoparticle growth control, dusty plasma diagnostics, plasma nanotechnology.

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Introduction

Plasma-enhanced chemical vapor deposition (PECVD) is one of the most versatile methods for the formation of thin films, nanostructures, and functional coatings. This is because low-temperature plasma significantly expands the range of possible chemical reactions and enables controlled material growth near the substrate surface [1–6]. One of the key advantages of PECVD over thermal deposition methods is its ability to operate at reduced temperatures, which is particularly important for temperature-sensitive substrates and for preventing defect formation, diffusion processes, and degradation of the substrate material [7, 8]. Additional advantages of PECVD include high deposition rates, the possibility of forming graded and multilayer structures, and the ability to control interfacial regions and film microstructure. These features make PECVD a highly attractive technique for micro- and nanotechnology applications [9].

The efficiency of the PECVD process is determined by a combination of technological parameters, including pressure, RF discharge power, gas flow rate and gas ratio, substrate temperature, and the condition of the plasma reactor [7, 10]. For this reason, modern PECVD studies increasingly employ in situ diagnostic techniques, such as optical emission spectroscopy (OES), mass spectrometry, and analysis of the electronic parameters of the plasma, in order to correlate the plasma composition with the morphology, structure, and electrical properties of the deposited coatings [10–13]. For instance, several studies have shown that pulsed precursor injection and controlled dilution regimes, such as hydrogen dilution, can be used to finely tune the growth, densification, and transition stages from an amorphous to a nanocrystalline structure [14, 15].

In such experimental systems, LabVIEW provides a convenient software environment for measurement automation, actuator control, and real-time feedback implementation [16–18]. Published studies have demonstrated its use for automatic acquisition of plasma probe characteristics, rapid calculation of electron parameters, continuous processing of diagnostic signals, and process control according to predefined quality criteria. These capabilities are particularly useful for investigating plasma-chemical processes and synthesizing nanostructures [19]. Thus, the use of LabVIEW in PECVD experiments can improve process reproducibility, reduce operator influence, and provide a more accurate correlation between plasma parameters and the properties of the synthesized material [20].

When moving from conventional PECVD processes to the synthesis of nanoparticles directly in plasma, it is important to emphasize that the plasma environment acts not only as an energy source, but also as a tool for controlling nanoparticle nucleation, evolution, and subsequent assembly into the desired structure [2, 21–23]. In such processes, control over individual stages of material formation is especially important, since the final size, morphology, uniformity, and functional properties of nanoparticles are largely determined during nucleation, growth, charging, and coagulation.

The practical importance of continuous process monitoring is related to the fact that variations in plasma parameters, such as current, pressure, gas composition, and temperature, can significantly affect particle size and the competing mechanisms of particle formation and enlargement [24]. In studies on oxide nanoparticle synthesis in thermal plasma, in situ spectroscopy has been shown to directly correlate particle size with plasma parameters, while the spectral characteristics of the plasma column provide insight into the growth mechanism. Therefore, monitoring each stage of synthesis is necessary not only to obtain a target average particle size, but also to narrow the size distribution, improve reproducibility, and prevent undesirable agglomeration.

This is where LabVIEW becomes particularly useful, as it enables diagnostics, visualization, data logging, and feedback control to be integrated into a single experimental control system [16, 17]. This makes it possible to move from passive observation to active control of the synthesis process, where plasma parameters can be adjusted in real time based on diagnostic data, making the process more stable and predictable [10, 25].

For the vacuum subsystem of a PECVD setup, LabVIEW is especially valuable as a platform that combines control and recording of key process parameters. This is because the quality of deposition is determined not only by the plasma itself, but also by the stability of pressure, gas flow, chamber temperature, and the previous operating history of the reactor [7,10]. In automated systems, LabVIEW has already been used for computerized hardware control and process logging, demonstrating its suitability for building flexible control systems for vacuum–plasma equipment [26].

In practice, LabVIEW makes it possible to implement a step-by-step operating algorithm for the experimental setup, including chamber evacuation, pressure stabilization, working gas supply, discharge ignition, mode switching, and emergency shutdown when process parameters exceed the allowable limits [27, 28]. In addition, LabVIEW is convenient for in situ data acquisition from pressure, flow, voltage, and current sensors, as well as for integrating plasma diagnostics and real-time feedback. This improves reproducibility and simplifies control over the individual stages of synthesis.

Materials and methods

Full Automation of Experimental Process

To implement automated control of nanomaterial synthesis by PECVD, a control system based on the LabVIEW software environment was developed. In this work, LabVIEW was used as the central platform for coordinating all major stages of the experiment, from vacuum chamber preparation and pressure monitoring to gas supply control, RF discharge ignition, execution of the predefined synthesis scenario, and storage of technological parameters. The choice of LabVIEW was motivated by its wide use in automated measurement and control systems, its ability to interface with different instruments, and its capabilities for user-interface development and real-time experimental data acquisition.

The automated PECVD synthesis cycle begins with preparation of the reaction chamber. At the first stage, the system evacuates the chamber to a predefined base pressure while continuously monitoring the vacuum gauge readings. Transition to the next stage is allowed only after the required pressure value has been reached, ensuring identical initial conditions for each experimental series. This approach is particularly important for plasma-chemical processes, since pressure, gas composition, and the condition of the chamber directly affect discharge stability and the properties of the resulting material. PECVD studies also indicate that process parameters, including pressure, gas environment, and RF power, are key factors controlling thin-film deposition and the plasma process as a whole.

After the base pressure is reached, LabVIEW automatically initiates the supply of the working gas or gas mixture into the reactor. At this stage, the system monitors the pressure variation inside the chamber and ensures that the required working pressure for subsequent plasma ignition is achieved. After pressure stabilization, the gas supply can either be stopped or switched to a predefined flow mode, depending on the selected synthesis scenario. Thus, preparation of the gas environment is performed not manually, but according to a predefined algorithm, which reduces operator influence and improves the reproducibility of experimental conditions. A similar automation principle, based on sequential control of temperature, pressure, and gas flows, is widely used in CVD/PECVD systems to improve process stability and repeatability [29, 30].

After the required vacuum-gas conditions have been established, the system proceeds to the plasma ignition stage. LabVIEW turns on the RF generator according to the predefined scenario and then controls the sequence of technological operations required for the synthesis process. At this stage, the program functions not only as an operator interface, but also as a logical controller that determines the order of transitions between the process stages. This approach makes it possible to represent PECVD synthesis as a set of interconnected technological states, where each subsequent stage starts only after the predefined conditions of the previous stage have been fulfilled.

The main advantage of the developed system is that the entire synthesis process is carried out automatically according to a predefined algorithm. This minimizes manual intervention, reduces the probability of operator errors, and ensures repeatable experimental conditions. In automated PECVD systems, such an approach is used to implement both semi-automatic and fully automatic operating modes, contributing to improved film uniformity and reproducibility of the properties of the obtained materials [31]. In addition, automatic logging of process parameters enables the creation of a digital record for each experiment, including evacuation time, chamber pressure, gas inlet timing, working pressure, plasma ignition parameters, duration of individual process stages, and total synthesis time.

The automated PECVD synthesis algorithm includes the following steps:

1. Pumping of the vacuum chamber to the base pressure.
2. Real-time pressure monitoring.
3. Gas inlet until the target working pressure is reached.
4. Stabilization of the working pressure or interruption of the gas flow according to the selected synthesis scenario.
5. RF plasma ignition under predefined power conditions.
6. Execution of the programmed synthesis scenario.
7. Automatic shutdown of the plasma after the defined process time.
8. Final pumping of the chamber.
9. Logging and saving of the technological parameters for further analysis.

Gas Flow Control and MFC Interface Implementation

An important part of the automated PECVD control system is the regulation of the working gas flow before plasma ignition. In the developed LabVIEW program, several approaches were implemented for controlling mass flow controllers (MFCs), depending on the available communication interface of each device. This was necessary because different MFC models support different control modes, including analog voltage input and digital communication through RS-232. In many commercial MFCs, the setpoint can be supplied through an analog input, commonly in the range of 0–5 V, where the applied voltage corresponds to a certain fraction of the full-scale flow range. For example, most of the manuals describe a standard 0–5 Vdc analog setpoint input applied to a specific connector pin, while MKS documentation also describes MFC versions with analog setpoint and analog flow signals in the 0–5 Vdc range.

At the first stage, several MFCs were tested using an analog control scheme. In this configuration, LabVIEW generates a control signal that is applied to the analog input pin of the MFC. However, this approach has an important limitation: if the system applies only a fixed high-level signal, for example 5 V, the controller interprets this as a full-scale setpoint and opens the flow to the maximum calibrated range. Therefore, analog control is suitable only when the voltage can be precisely generated and scaled according to the required flow rate. In this case, the desired flow rate can be converted into a voltage setpoint using a calibration relationship:

$$V_{set} = 5 \times \frac{Q_{set}}{Q_{FS}} \quad (1)$$

where V_{set} is the analog voltage applied to the MFC, Q_{set} is the required gas flow rate in sccm, and Q_{FS} is the full-scale range of the controller. Without such voltage scaling, analog control becomes closer to an on/off mode and does not provide accurate regulation of the gas flow, which is critical for reproducible PECVD synthesis.

A more flexible control approach was implemented for MFCs equipped with an RS-232 interface. In this case, a dedicated LabVIEW driver was developed for communication with a specific MFC model. The driver provides serial communication between the computer and the controller, initializes the COM port, sends the required setpoint command, and reads the actual flow response from the device. This approach is consistent with the general LabVIEW instrument-control architecture, where NI-VISA is used for communication with serial instruments through RS-232, RS-422, or RS-485 interfaces. NI documentation also notes that serial communication in LabVIEW requires correct port configuration, including baud rate, stop bits, parity and device-specific command format [32, 33].

The developed gas-flow control module provides two operation modes: analog voltage-based control for MFCs without digital communication and RS-232-based control for digitally accessible MFCs. The RS-232 approach was found to be more suitable for automated PECVD experiments because it enables direct assignment of the required gas flow, reduces the probability of over-opening the valve, and improves the reproducibility of the gas environment before plasma ignition. This module is integrated into the general LabVIEW-based PECVD algorithm, where the gas flow is controlled together with chamber pressure, pumping sequence, plasma ignition and the subsequent synthesis scenario.

Figure 1 – Front diagram for gas flow control

Figure 1 shows an example of the LabVIEW front panel developed for controlling the flow of the plasma-forming gas. As shown in the interface, the operator sets the ‘Setpoint Input’ value in the range of 0–5 V, where 5 V corresponds to the full-scale opening of the MFC and therefore to the maximum available gas flow. The control voltage is supplied to the corresponding MFC input pin using a National Instruments 24-channel, 8.5 mA I/O device, which provides stable and reliable analog signal generation for gas-flow control. The front panel also includes a graphical indicator for monitoring the gas-flow control state, allowing the operator to observe the process in real time and stop it if necessary.

Pressure-Controlled Vacuum and Gas Preparation Sequence

After implementation of the gas-flow control module, the next stage of the LabVIEW-based PECVD system was the automation of vacuum and gas preparation before plasma ignition. This stage is critical because the initial pressure, gas composition, and stabilization time define the starting conditions for plasma formation and strongly influence the reproducibility of the synthesis process. In the developed system, LabVIEW acts as the central control environment that coordinates the vacuum pump, gas inlet line, pressure sensor, MFCs, and plasma ignition sequence. This approach is consistent with the general purpose of LabVIEW as a graphical environment for automated test, measurement, instrument connectivity, user-interface development, and data acquisition.

The automated procedure begins with evacuation of the PECVD chamber to a predefined base pressure. During this stage, the pressure signal is continuously acquired and displayed in the LabVIEW front panel. The program does not allow transition to the next stage until the measured pressure reaches the required threshold. This condition-based transition is important because it ensures that each synthesis experiment starts from comparable vacuum conditions. After the base pressure is achieved, LabVIEW opens the gas inlet line and sends the required flow setpoint to the selected mass-flow controller. Depending on the MFC interface, this setpoint can be generated either as an analog signal or as a digital command through RS-232 communication.

For MFCs with analog input, the gas-flow setpoint is controlled by applying a voltage signal, typically in the 0–5 V range. In such controllers, the applied voltage is proportional to the full-scale flow range; therefore, 5 V corresponds to the maximum calibrated flow of the device. This type of analog signal is commonly used in commercial mass-flow controllers, while digital MFCs may also support serial communication for direct setpoint programming. However, analog control requires careful voltage scaling. If a fixed 5 V signal is applied without conversion from the required flow rate, the MFC opens to its full-scale range, which can disturb the working pressure and reduce the reproducibility of the PECVD process.

To overcome this limitation, an RS-232-based control mode was implemented for digitally accessible MFCs. In this case, a dedicated LabVIEW driver was developed for the selected controller. The driver initializes the serial port, sends the gas-flow setpoint directly in engineering units, such as sccm, reads the actual flow response, and closes the communication session after the operation. The advantage of this approach is that the operator or program can define the desired gas flow directly in the LabVIEW block diagram without manual conversion to voltage. Commercial MFCs with serial interfaces are designed for such programmable functions, including flow setpoint control and reading of flow-related parameters.

After gas injection, the system continuously monitors the chamber pressure until the target working pressure is reached. The transition to the plasma ignition stage is performed only when the pressure remains within a predefined tolerance range for a selected stabilization time. This logic can be described by the following condition:

$$|P(t) - P_{set}| < \Delta P \quad \text{for} \quad t \geq t_{stab} \tag{2}$$

where $P(t)$ is the measured chamber pressure, P_{set} is the target working pressure, ΔP is the allowed pressure deviation, and t_{stab} is the stabilization time. This condition prevents premature plasma ignition under unstable gas-pressure conditions and improves the repeatability of the synthesis process.

Such pressure-controlled preparation is important for PECVD because deposition pressure can significantly affect the properties of the deposited material. For example, studies on RF-PECVD thin-film growth have shown that changes in deposition pressure can strongly influence film thickness, bonding structure, optical properties, and morphology [34]. Therefore, automatic control of the pressure and gas-flow sequence is not only a technical feature of the LabVIEW program but also an essential requirement for obtaining reproducible nanomaterials.

Therefore, automatic control of the pressure and gas-flow sequence is not only a technical feature of the LabVIEW program but also an essential requirement for obtaining reproducible nanomaterials [35]. In the present PECVD system, this logic allows the operator to define the experimental scenario in advance, while LabVIEW executes each stage automatically and records the corresponding technological parameters.

As a result, the automated vacuum–gas preparation module reduces manual intervention, prevents uncontrolled gas admission, and ensures that plasma ignition occurs only under predefined and stable process conditions. This makes the LabVIEW system not only a control interface but also a process-management platform for reproducible PECVD synthesis of nanomaterials.

Results and discussion

RF Matching & Cyclic growth Control

To control the nanomaterial synthesis process by PECVD, a universal LabVIEW block diagram was developed for the first stage of the experiment, namely RF matching (Figure 2a). At this stage, the RF plasma is ignited at a specified power, which is selected according to the specific experimental objective. It should be emphasized that minimization of reflected power is one of the key requirements for stable ignition and sustained operation of RF plasma in the PECVD process. During the discharge, the plasma behaves as a dynamically changing load whose impedance depends on pressure, gas-mixture composition, supplied RF power, electrode surface condition, and the current stage of film or nanomaterial growth [36]. When the impedance is not properly matched, a fraction of the applied RF power is reflected back to the generator. This reduces the effective power absorbed by the plasma and may lead to discharge instability, fluctuations in plasma parameters, changes in the deposition rate, and deterioration in the reproducibility of the synthesized nanomaterial properties [37,38]. Therefore, in the automated PECVD control system, monitoring the forward and reflected RF power, as well as adjusting the RF matching unit, is essential for maintaining a stable plasma environment and ensuring the quality of the obtained materials.

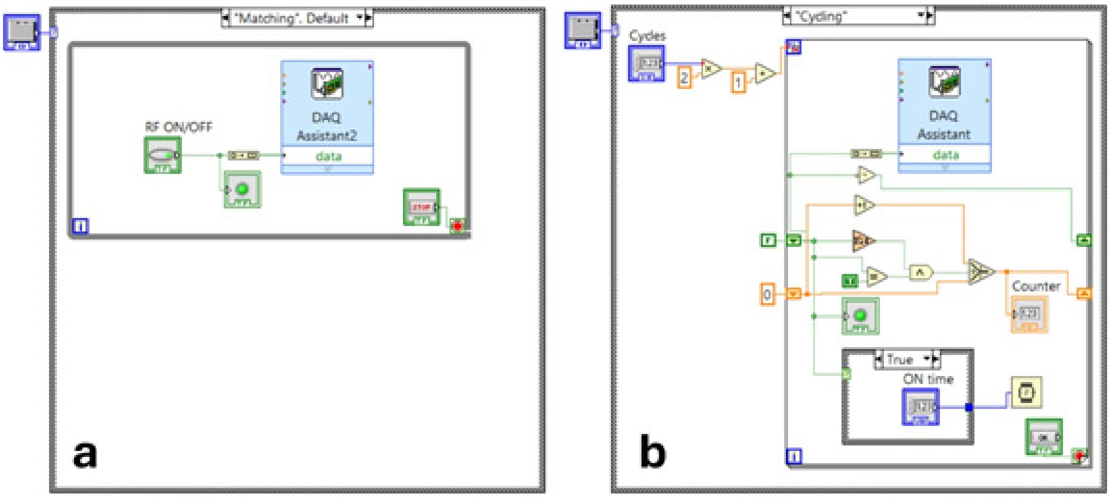

Figure 2 – Block diagram for RF matching following with synthesis process control

The second stage of automated control in the PECVD-based nanomaterial synthesis process is related to setting the parameters of cyclic nanomaterial growth (Figure 2b). At this stage, the main time parameters of the process are defined in LabVIEW: the plasma-on time, the plasma-off time, and the total number of growth cycles. During the plasma-on time period, the gas mixture is activated, precursor molecules are dissociated, chemically active radicals and ions are formed, and nanoparticle nucleation and growth occur in the plasma volume. After the plasma is switched off, the particles lose their charge, leave the confinement region governed by the plasma potential, and are deposited onto the substrate surface, for example, onto a Si substrate intended for subsequent analysis by SEM, TEM, AFM, Raman spectroscopy, XPS, or other analytical techniques. A similar mechanism of cyclic nanoparticle deposition has been demonstrated for PECVD synthesis of carbon nanostructures, where the number of particles deposited on the surface is controlled by the number of cycles, while the surface morphology depends on the cycle duration and plasma parameters [39–41].

For operator convenience, a Counter tool was also added to the LabVIEW interface to display the current number of the synthesis cycle being performed.

Control of the plasma-on and plasma-off times is an important tool for regulating the size, concentration, and spatial distribution of nanoparticles. In particular, for silicon nanoparticle synthesis by VHF-PECVD, it has been shown that pulsed plasma operation can produce particles with a narrow size distribution, while variation of the plasma-off time can be used to control nanoparticle size [42]. Therefore, in the developed LabVIEW system, the cyclic growth mode is implemented as a controlled sequence of operations that includes setting the plasma ignition time, pause duration, number of repeated cycles, and automatic logging of process parameters [12]. This approach improves synthesis reproducibility, enables controlled accumulation of material on the substrate, and allows the automated control parameters to be correlated with the final morphological and structural characteristics of the obtained nanomaterials [43, 44].

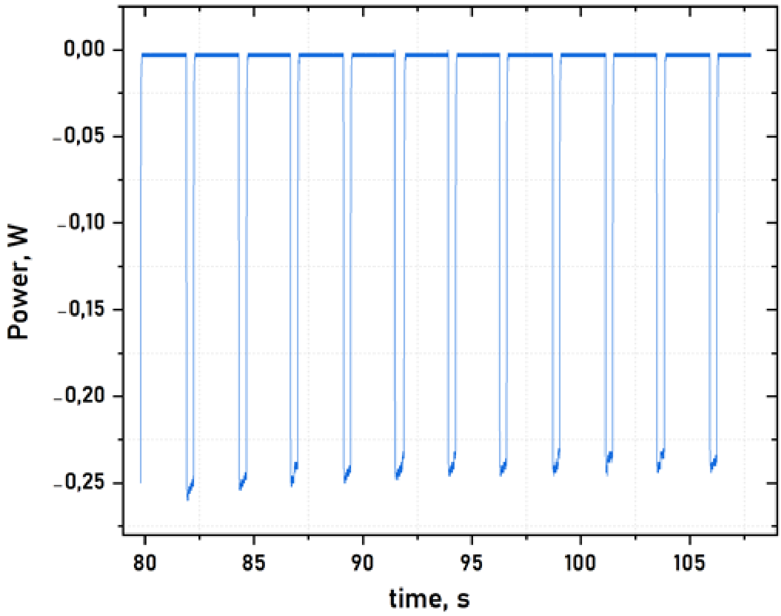

Figure 3 – Time evolution of PECVD process

Figure 3 shows representative time-dependent changes in the main technological and diagnostic parameters during the automated PECVD cycle. The oscillograph reflects the automated RF cycling the PECVD process for nanoparticle synthesis. The parameters were as follows: plasma on/off times 200 ms and 2000 ms, accordingly. As it was mentioned before, the time control is also possible to maintain by the user. The gas flow for 2 types of gases was 40 sccm and 5 sccm for nitrogen and methane gases, accordingly. As the graph shows, the plasma on and off times were correctly controlled.

Monitoring of the nanoparticle cloud density

The final stage of the developed LabVIEW-based PECVD control system was focused on the optical monitoring of nanoparticle cloud density in dusty plasma. This module was implemented to provide an in-situ diagnostic of the nanoparticle cloud formed during plasma-assisted synthesis. In contrast to ex situ methods such as SEM or TEM, which provide information only after particle deposition on a substrate, optical monitoring makes it possible to follow the temporal evolution of nanoparticles directly during the plasma process. This is especially important for dusty plasma systems, where the formation, charging, growth and transport of nanoparticles can significantly affect the plasma parameters and the final properties of the synthesized material.

The monitoring principle is based on measuring the change in laser radiation intensity caused by the interaction of the laser beam with nanoparticles suspended in plasma volume. In the developed system, the laser beam passes through the dusty plasma region, while the optical signal is detected by a photodetector connected to a Keithley measuring unit and recorded automatically using LabVIEW. The signal is measured before significant nanoparticle growth and then during or after the growth stage. The difference between the initial and final optical intensities is used as an indicator of nanoparticle cloud formation and can be further related to the particle number density. The relationship between the laser signal and nanoparticle cloud density is based on the attenuation of laser radiation passing through the plasma region. When nanoparticles are formed and suspended in the plasma volume, they scatter and partially absorb the incident laser light. As a result, the transmitted laser intensity decreases compared with the initial intensity measured before significant nanoparticle formation. Therefore, the change in laser intensity can be used as a relative diagnostic parameter characterizing the formation and temporal evolution of the nanoparticle cloud. In the present work, the optical signal is used mainly for relative in situ monitoring. Absolute determination of nanoparticle number density would require additional calibration, including information about particle size, optical properties, and the effective interaction length of the laser beam with the nanoparticle cloud.

A similar laser attenuation approach was used by Ongaibergenov et al. to determine the time-dependent evolution of carbon nanoparticle cloud density and size in dusty glow discharge plasma; in that work, the laser signal was detected by a silicon photodiode, while signal acquisition and intensity analysis were performed using NI LabVIEW and a Keithley 2401 measuring unit (Figure 4) [12].

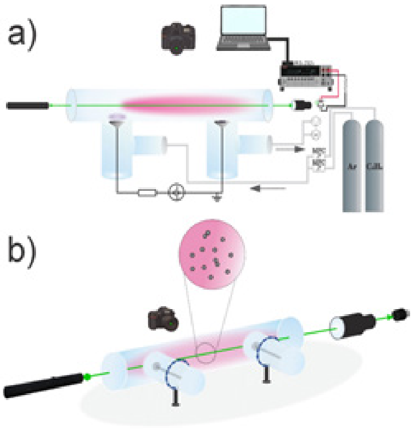

Figure 4 – Schematic diagram of the experimental setup for monitoring
the density of the carbon nanoparticle cloud during the synthesis process

In the present work, the novelty is not only the use of optical diagnostics itself, but its integration into the automated LabVIEW control architecture. The photodetector signal is continuously converted into a photocurrent or voltage signal by the Keithley unit and transferred to LabVIEW, where it is displayed, stored and synchronized with other technological parameters of the PECVD process. These parameters include chamber pressure, gas-flow state, RF power, plasma ignition time, plasma-on/plasma-off cycle duration and total synthesis time. Therefore, each synthesis experiment produces a digital dataset that links the optical response of the nanoparticle cloud with the controlled plasma-growth conditions.

The use of laser-based diagnostics for dusty plasma and plasma-grown nanoparticles is well established. Boufendi et al. noted that laser light scattering is one of the most widely used techniques for detecting and sizing nanoparticles during their growth in dusty plasma systems [45]. In addition, Ouaras et al. demonstrated that time-resolved in situ laser extinction and scattering diagnostics can be used together with SEM and plasma diagnostics to study nanoparticle synthesis and transport in low-pressure plasma. Their results showed that the decrease in laser transmission is correlated with changes in nanoparticle cloud density and size, and that laser scattering imaging can reveal the spatial structure of the nanoparticle cloud, including void formation [46].

The importance of nanoparticle monitoring is also supported by studies showing that particle growth changes the plasma state itself. Ussenov et al. investigated nanodust-containing argon-acetylene RF plasmas and showed that cyclic nanoparticle growth affects electron density, electron temperature and plasma potential; they also used laser light scattering to confirm the presence of the dust particle cloud near the probe region [47]. This confirms that optical monitoring of the nanoparticle cloud is not only a material-diagnostics tool, but also an important method for understanding how nanoparticle formation modifies the plasma environment during synthesis.

Thus, the developed LabVIEW-based optical monitoring module provides an additional feedback channel for the automated PECVD system. While the previous modules control the vacuum preparation, gas admission, RF matching and cyclic plasma growth, this final module records the optical response of the nanoparticle cloud and allows the nanoparticle cloud density evolution to be evaluated. The integration of this diagnostic into LabVIEW makes it possible to move from simple process automation toward data-driven plasma synthesis, where the growth of nanomaterials can be correlated with real-time optical signals and controlled technological parameters.

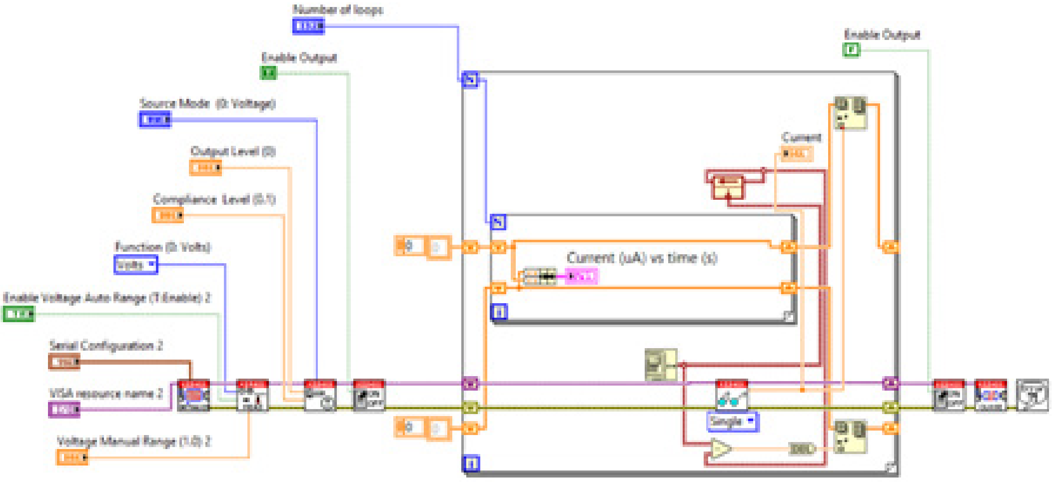

Figure 5 – LabVIEW block diagram for optical monitoring of nanoparticle cloud density in dusty plasma

Figure 5 shows the LabVIEW block diagram for the optical monitoring module, in which communication with the Keithley 2401 measuring unit is established via the RS-232 interface. This module records the photocurrent signal from the photodetector through the Keithley unit and evaluates the change in laser intensity caused by the nanoparticle cloud formed during plasma synthesis.

Conclusion

In this work, a LabVIEW-oriented automated control system for the PECVD synthesis of nanomaterials was developed and described. The main result of the study is the creation of a unified control algorithm that covers the complete experimental cycle: from vacuum chamber preparation and working gas supply to plasma ignition, cyclic growth implementation, and optical signal acquisition from nanoparticles formed in the plasma volume. This approach transforms the PECVD experiment from manual control of individual devices into a sequential, programmable, and reproducible technological process. The scientific novelty of this work lies in the development of a unified LabVIEW-based control algorithm for PECVD nanomaterial synthesis, where several technological and diagnostic modules are integrated into a single automated platform. Unlike partial automation of individual instruments, the proposed system combines vacuum chamber preparation, pressure-controlled gas admission, MFC control through analog and RS-232 interfaces, RF plasma ignition and matching, cyclic growth control, optical monitoring of nanoparticle cloud evolution, real-time visualization, and data logging. This integrated approach makes it possible to transform the PECVD process into a sequential, programmable, and reproducible digital synthesis cycle.

At the first stage, automation of the vacuum–gas preparation procedure was implemented. LabVIEW provides continuous pressure acquisition, monitors the achievement of the base vacuum level, and allows the system to proceed to the next stage only after the predefined condition has been fulfilled. This prevents the process from being initiated under unstable initial conditions and improves experimental repeatability. In addition, a working-pressure stabilization logic was implemented before plasma ignition, which is particularly important for PECVD because pressure and gas composition directly influence discharge parameters, deposition rate, and the properties of the formed material.

Another important result is the development of a gas-flow control module based on mass flow controllers. Two practical connection modes were considered: analog control using a 0–5 V signal and digital control via RS-232 communication. The analog mode can be used for MFCs without a digital interface; however, it requires accurate conversion of the required gas flow into the corresponding control voltage. Otherwise, applying a high-level signal, such as 5 V, results in full-scale opening of the controller and disrupts the required gas-supply regime. The RS-232 mode was found to be more effective, and a dedicated communication driver was developed for this purpose. In this case, the gas flow rate is specified directly in sccm, while LabVIEW sends the command to the device and receives feedback on the flow status. This improves control accuracy, reduces the risk of uncontrolled gas admission, and makes the process more convenient for automation.

The next module of the system is related to RF plasma control. LabVIEW is used to ignite the discharge according to a predefined scenario and to control the RF matching stage. Minimization of reflected power is essential because impedance mismatch between the RF generator and the plasma load reduces the effective power absorbed by the plasma and may cause discharge instability. Integrating RF matching into the general automated control algorithm improves the stability of the plasma process and provides more reproducible conditions for nanomaterial growth.

A cyclic growth module was also implemented, in which the plasma-on time, pause duration, and total number of cycles are defined. This structure makes it possible to control not only the plasma ignition event itself, but also the temporal architecture of the synthesis process. During the plasma-on period, the gas environment is activated and nanoparticles are formed, whereas during the pause, conditions are created for their deposition onto the substrate. The presence of a cycle counter and automatic time logging makes this mode convenient for systematic variation of process parameters and their subsequent comparison with SEM, TEM, AFM, Raman, XPS, and other analytical results.

The final element of the system is an optical monitoring module for evaluating the density of the nanoparticle cloud in dusty plasma. This module records changes in the intensity of laser radiation interacting with nanoparticles in the plasma volume. The photodetector signal is measured using a Keithley 2401 unit and transferred to LabVIEW, where it is stored together with the synthesis parameters. This makes it possible to correlate the dynamics of nanoparticle formation with pressure, gas supply, plasma-on time, number of cycles, and RF discharge parameters.

Thus, the developed system demonstrates that LabVIEW is an effective tool for complete automated control of PECVD-based nanomaterial synthesis. Its key advantage lies in the integration of control, diagnostics, visualization, and data logging within a single platform. This reduces operator influence, improves experimental reproducibility, provides a digital record of each synthesis process, and creates a basis for the further transition toward intelligent plasma-process control based on feedback and experimental data analysis. Moreover, the developed LabVIEW-based automation platform can serve as a basis for future implementation of feedback control algorithms using diagnostic signals such as pressure, gas flow rate, RF forward/reflected power, and optical monitoring data. Also, it should be noted that machine learning approaches may be used in future work to predict optimal synthesis parameters and improve the control strategy of nanoparticle growth in plasma environments.

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ПЛАЗМАЛЫҚ ОРТАДАҒЫ НАНОБӨЛШЕКТЕР СИНТЕЗІН LABVIEW КӨМЕГІМЕН АВТОМАТТЫҚ БАСҚАРУ

Аңдатпа

Берілген жұмыста LabVIEW бағдарламалық ортасы негізінде іске асырылған газ фазасынан плазмалық-химиялық тұндыру әдісімен наноматериалдарды синтездеу процесін автоматты бақылау жүйесі ұсынылған. Зерттеудің негізгі мақсаты – PECVD процесінің негізгі кезеңдерін дәйекті басқаруды қамтамасыз ететін бірыңғай бағдарламалық және аппараттық платформаны әзірлеу: вакуумдық камераны дайындау, қысымды бақылау, жұмыс газын беру, ЖЖ плазмасын жағу, ЖЖ қуатын үйлестіру, наноматериалдардың циклдік өсуі және плазмалық ортадағы нанобөлшектерді оптикалық бақылау. LabVIEW пайдалану атқарушы құрылғыларды басқаруды, эксперименттік параметрлерді тіркеуді және процесті нақты уақыт режимінде визуализациялауды біріктіруге мүмкіндік берді. Автоматтандырылған цикл жұмыс камерасын белгіленген қысымға келтіруден басталады. Келесі кезең эксперименттің қайталанатын бастапқы шарттарын қамтамасыз ететін белгіленген шекті мәнге жеткеннен кейін ғана жүзеге асырылады. Әрі қарай, бағдарлама газ шығынын басқару құрылғысы арқылы жұмыс газын беруді басқарады. Жұмыста газ ағынын басқарудың екі режимі қарастырылған: 0–5 В кернеумен аналогтық режим және RS-232 арқылы цифрлық байланыс режимі. Аналогтық әдіс басқару кернеуін дәл масштабтауды қажет ететіні көрсетілген, өйткені 5 В кернеу беру контроллердің максималды ағынға толық ашылуына әкеледі. Сонымен қатар, RS-232 интерфейсі шығынды sccm бірліктерінде тікелей орнатуға мүмкіндік береді, бұл газ ортасын басқарудың дәлдігі мен ыңғайлылығын арттырады. Қысым тұрақтандырылғаннан кейін LabVIEW ЖЖ разрядын жағып, шағылған қуатты азайтуға және плазмалық процестің тұрақтылығын арттыруға бағытталған RF matching алгоритмін орындайды. Бағдарламаның жеке модулінде наноматериалдардың циклдік өсу режимі жүзеге асырылған, яғни плазманың жану уақыты, кідіріс уақыты және циклдер саны теңшеледі. Бұл тәсіл наноматериалдардың жиналуын бақылауға және процесс параметрлерін алынған наноқұрылымдардың морфологиялық сипаттамаларымен байланыстыруға мүмкіндік береді. Жүйенің соңғы модулі тозаңды плазмадағы нанобөлшектер бұлтының тығыздығын оптикалық бақылауға арналған. Ол үшін RS-232 арқылы LabVIEW-пен байланысқан Keithley 2401 фотодетекторы мен өлшеу блогы арқылы плазма аймағынан өткен лазерлік сәулелену қарқындылығының өзгеруі тіркеледі. Бастапқы және өзгертілген сигнал қарқындылықтарының айырмашылығы нанобөлшектердің пайда болуы мен эволюциясының диагностикалық параметрі ретінде қолданылады. Әзірленген жүйе LabVIEW бағдарламасының жеке құрылғыларды автоматтандыру үшін ғана емес, сонымен қатар наноматериалдардың PECVD синтезін басқарудың толық цифрлық циклін құру үшін де тиімді қолданылатынын көрсетеді.

Түйін сөздер: PECVD, автоматты плазмалық синтез, нанобөлшектер өсуін бақылау, тозаңды плазма диагностикасы, плазмалық нанотехнология.

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АВТОМАТИЧЕСКОЕ УПРАВЛЕНИЕ СИНТЕЗОМ НАНОЧАСТИЦ В ПЛАЗМЕННОЙ СРЕДЕ С ИСПОЛЬЗОВАНИЕМ LABVIEW

Аннотация

В работе представлена система автоматического контроля процесса синтеза наноматериалов методом плазменно-усиленного химического осаждения из газовой фазы, реализованная на основе программной среды LabVIEW. Основная цель исследования заключается в разработке единой программно-аппаратной платформы, обеспечивающей последовательное управление ключевыми стадиями PECVD-процесса: подготовкой вакуумной камеры, контролем давления, подачей рабочего газа, зажиганием ВЧ-плазмы, согласованием ВЧ-мощности, циклическим ростом наноматериалов и оптическим мониторингом наночастиц в плазменной среде. Использование LabVIEW позволило объединить управление исполнительными устройствами, регистрацию экспериментальных параметров и визуализацию процесса в режиме реального времени. Автоматизированный цикл начинается с откачки реакционной камеры до заданного базового давления. Переход к следующей стадии осуществляется только после достижения установленного порогового значения, что обеспечивает воспроизводимые начальные условия эксперимента. Далее программа управляет подачей рабочего газа через газовый расходомер. В работе рассмотрены два режима управления газовым потоком: аналоговый режим с подачей напряжения 0–5 В и цифровой режим связи через RS-232. Показано, что аналоговый способ требует точного масштабирования управляющего напряжения, поскольку подача 5 В приводит к полному открытию контроллера на максимальный расход. В то же время RS-232-интерфейс позволяет задавать расход непосредственно в единицах sccm, что повышает точность и удобство управления газовой средой. После стабилизации давления LabVIEW инициирует запуск ВЧ-разряда и выполняет алгоритм RF matching, направленный на минимизацию отраженной мощности и повышение стабильности плазменного процесса. Отдельный модуль программы реализует циклический режим роста наноматериалов, где задаются время горения плазмы, время паузы и количество циклов синтеза. Такой подход позволяет контролировать накопление материала на подложке и связывать параметры процесса с морфологическими характеристиками получаемых наноструктур. Завершающий модуль системы предназначен для оптического мониторинга плотности облака наночастиц в пылевой плазме. Для этого используется регистрация изменения интенсивности лазерного излучения, прошедшего через область плазмы, с помощью фотодетектора и измерительного блока Keithley 2401, связанного с LabVIEW через RS-232. Разница между исходной и измененной интенсивностью сигнала используется как диагностический параметр формирования и эволюции наночастиц. Разработанная система демонстрирует, что LabVIEW может эффективно применяться не только для автоматизации отдельных приборов, но и для построения полного цифрового цикла управления PECVD-синтезом наноматериалов.

Ключевые слова: PECVD, автоматизированный плазменный синтез, контроль роста наночастиц, диагностика пыелвой плазмы, плазменная нанотехнология.