Instrumentation
China Instrument and Control Society
OPEN ACCESS
INSTRUMENTATION, Vol. 11, No. 2, June 2024 https://doi.org/10.15878/j.instr.202400195

Article

Polarization Band Effect and MEMS-Based Plasma Generation

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Abstract: We find that effects resulting from micro/nano scale structures can regulate space charges which excite and lead to the special electric field distribution featuring the flux convergence band structure. It is here referred to as the polarization band effect, which stems from the specific field-induced interactions among atoms and molecules. The micro/nanoelectrode array structures were designed and fabricated using the non-silicon micro/nano processing technology, forming micro/nano electrode arrays-based plasma microelectromechanical systems (NPMEMS). The integrated NPMEMS device can be used to regulate the inner energy states of matters and generate plasma based on the polarization band effect, all within a single chip-size limited local area or extending into a large volume space with the deployment of a distributed array of multiple devices. Its special physical and chemical properties can be utilized to greatly improve the efficiency of potential application systems or solve mechanism-level challenges in plasma-related applications of multiple fields.

Keywords: polarization band effect, MEMS; micro/nanoelectrode array; plasma

Citation: Henggao Ding, and Zhongyu Hou. "Polarization Band Effect and MEMS-based Plasma Generation." Instrumentation 11, no. 2 (June 2024). https://doi.org/10.15878/j.instr.202400195.

1 Physical principle and technological characteristics

The characteristics of plasma can be described in two aspects[1,2]: Firstly, in terms of matter, plasma contains unique components which are different from other states of matter, including free electrons, ions, and excited neutral particles. Secondly, from the perspective of energy, plasma, along with solid, liquid, and gas, is one of the states of matter. In terms of macroscopic statistical characteristics, its constituent particles possess higher energy than other states of matter, either partially or in the overall spatial region. In terms of the microscopic excitation relaxation process, the characteristic components of plasma typically have transient lifetimes and constantly enduring non-equilibrium thermodynamic processes, i.e., always in the process of rapid generation and disappearance. Consequently, a continuous supply of external energy is required for their existence or effectiveness as a functioning component, and the physical mechanism of energy supply depends on the microscopic interaction process of electromagnetic forces and the mesoscopic relaxation process of particle collisions.

Artificial plasma generally evolves from other states of matter, with the core process being the continuous provision of energy by an ionization source to separate the charges from the neutral particles of the ionized matter. Over the past century, the scientific and industrial communities have mainly developed three methodologies for generating plasma[2-8]: First, methods that rely primarily on the accelerated free electrons to collide and ionize, such as glow discharge, radio frequency microwave discharge, and high-energy electron beam discharge; Second, methods that primarily rely on heating gas molecules, such as alkali metal combustion and electric Joule heating; Third, methods that primarily rely on ionizing radiation to produce photoelectric ionization, such as ultraviolet photoelectric ionization and high-energy ray ionization. Due to the intensive difficulties in efficiently and controllable generating ionizing radiation, artificial plasma sources currently rely primarily on the first two methods, which physically depend on thermal effects: Microscopically, the fundamental mechanism roots in the conversion of the translational kinetic energy of free electrons and molecules into the internal orbital electron energy of molecules. Macroscopically, it manifests as local heat generation, heat transfer, and thermodynamic energy conversion, leading to significant and inhomogeneous entropy increases in the system overall. There is a fundamental contradiction between the increase in the chaotic level of a system and the designability, controllability, and efficiency of its thermodynamic state. This principle results in inherent limitations such as high power consumption, high temperatures, and stringent application conditions for the spatial expansion of plasma generation scope or the increase in electron density. These limitations represent one of the crucial mechanistic obstacles in the technological application of plasma.

The fundamental idea of micro-nano electrode array (MNEA) plasma source system originates from the research work conducted by Shanghai Jiao Tong University, exhibiting originality[9,10]. However, its relatively comprehensive kinetic and thermodynamic theoretical frameworks, along with the device-realization micro-nano technological system, have gradually developed since 2008 in response to the special aerospace application requirements for efficient and controllable novel plasma sources. The physical principles involve utilizing micro-nano integration processes to fabricate an electrode system composed of artificially designed micro-nano structures organized in a multi-layered high aspect ratio periodic array architecture, where a polarization band electric field (PBF) could be excited by the charge distribution governed by the MNEA structure. The PBEF fundamentally differs from the electric fields traditionally considered in the microscopic scale of the atoms or molecules, wherein uniformity exists in all three dimensions. In contrast, the PBEF exhibits an extremely intense electric field gradient in one dimension at the atomic scale, while maintaining microscopic and macroscopic uniformity in the other two dimensions. The formation of a PBEF does not necessarily require a strong electric field intensity. Instead, it involves controlling the mode of electromagnetic force acting on the atoms and molecules through the control of the spatial distribution of electromagnetic fields. The statistical effect of the polarization band electric field enables ordinary discharge media to be efficiently excited into a super-polarized medium with high excitation state density and leading to the polarization band effect (PBE). Under conditions of low power consumption and low average field strength, the PBE could produce and maintain a higher plasma density and higher spatial profile than the traditional discharges in the electric fields without the PBE. This makes it possible to develop plasma sources with compact size, low power consumption, and long-term stable operation.

The polarization band effect of a micro-nano electrode array is a kind of micro-nano structure-induced physical effect. The convergence of electric field flux in the micro-nano electrode array structure forms a polarization band electric field on one hand, and strengthens the surface electric field of the electrode system on the other hand. In the process of plasma evolution, the former leads to the polarization band process in the gas, which we call the polarization band electric field effect (PB-FE); the latter leads to the polarization band process on the electrode, which we call it the polarization band electrode effect (PB-EE). We collectively refer to both as the polarization band effect of the micro-nano electrode array. Theoretical and experimental studies have shown that they jointly determine the matter and thermodynamic state characteristics and evolution characteristics of polarization band effect plasma (PBEP) generation processes.

Under the influence of the polarization band electric field, there are two main processes for strongly polarized gas molecules to be excited into metastable states: First, strongly polarized molecules can maintain their orientational arrangement for a time-span in the PBF long enough to undergo the field-induced excitation through direct dipole-dipole interactions to form metastable states. Second, strongly polarized molecules are captured by the polarization band electric field and interact directly with the micro-nano electrodes to form metastable particles. The probability of spontaneous de-excitation of the metastable particles can be very low, resulting in a long lifetime and a large distance of diffusion and field-induced drifting[11,12]. Along their translational interaction pathways, high-flux-density, low-temperature soft ionization could be achieved through inelastic collisions with free electrons and other particle groups. Therefore, the polarization band electric field effect plays a critical role in efficiently transferring and delivering the energy of the PBF to the internal energy of orbital electrons. Firstly, due to the high quantum efficiency of excited transitions in strongly polarized molecules[13,14], the transfer and storage of energy from the PBF to the molecular internal structural degree of freedom could be highly efficient at the microscale. Secondly, since the ionization collision cross-section (probability) of the metastable particles is significantly higher than that of the ground states, regarding both the interactions with free electrons or heavy particles, the energy relaxation process from the preferentially energized components to the low-energy components could be highly efficient at the mesoscale. Thirdly, due to the energy of the PBF obtained by the metastable particles being 'stored' within the molecules, the thermodynamic temperature reflecting the translational energy requirement for the active ionization processes with free electrons and other particle populations is significantly reduced. The dissipation of a portion of the charge migration energy driven by the field in the form of random collisional Joule heat is significantly reduced, thus constituting a negative entropy flow in the evolution of matter states. This results in high efficiency in the generation and maintenance of plasmas at the macroscale. Theoretical calculations indicate that, by optimizing the distribution characteristics of the polarization band electric field without considering any constraints on specific implementations, the power consumption of micro-nano electrode array induced polarization band effect plasmas can be reduced by six orders of magnitude compared to that of the idealized Townsend's discharges in a flat-plane electrode system, while achieving the same free electron density of $1012/cm^3$ and the average electron temperature is reduced to 0.1~0.5 times lower. Besides, the average electron temperature in controlled local regions can be increased to 1~10 eV through partitioned and graded adjustment of the electric field distribution. Under current technological limitations and specific application scenarios, the measured power consumption can still be reduced by 2~4 orders of magnitude, i.e., under conditions of power consumption below 1W and a gas temperature rise of 1~10K, the free electron density can reach the order of $1014\sim1015/cm^3$. Supported also by the experimental observations, it is shown that the PB-FE determines the basic features of the resulted thermodynamic states and the modes of their evolution, serving as a decisive physical effect in the process of polarization band effect plasmas. The PB-EE is mainly related to the specific spatial and energy spectrum distribution patterns of the polarization band effect plasmas. Currently, we have primarily focused on selecting micro-nano electrode materials to optimize the thermodynamic stability of plasmas and enhance the controllability of the concentration distribution of chemically active species.

Polarization band electric field excites to form a special mode of energy transition from electromagnetic energy in free space into electromagnetic energy within molecule structures. We propose the quasi-particle model of 'polarization band exciton' to describe the basic law of polarization band effect on plasma state formation. Polarization band effect plasma is a state of matter that can transmit energy through polarization band excitons. Polarization band excitons are created due to the interaction between the polarization band electric field and the molecules, and they transmit the energy of the polarization band electric field through the collision relaxation processes with various particles such as the metastable molecules and the free electrons, or metastable molecules and ground state molecules. This quasi-particle allows a second mode of energy conversion in the evolution processes of polarization band effect plasma, besides free electrons, forming an important and special channel for energy conversion and transfer in the sense of physical kinetics. This channel enables the transfer of energy from various particles, including free electrons, to the interior structure of molecules through collisional relaxations, wherein the statistical characteristics are close to the behavior of the classical continuous interaction dynamics. In other words, the probability of converting translational kinetic energy into structural potential/kinetic energy inside the molecules will be significantly increased, thus forming a negative entropy 'cooling' link in the inevitable 'heating' entropy increase process of a plasma formation event. The mode of regulating and utilizing the internal energy of matter through polarization band excitons has general physical significance for efficiently controlling the state of matter. Compared with changing the state of matter through thermal effects, it does not require heating the matter to certain criteria first and then exciting and ionizing molecules through thermodynamic work still rooted in the translational energy heat transfer processes to achieve matter state and thermodynamic state transitions. Instead, it directly regulates the internal energy of molecular structure through structured electromagnetic forces. Compared with changing the state of matter through strong field effects such as pulsed lasers[15-19], it can achieve the work done on the internal structure of molecules by electromagnetic fields with a wider frequency spectrum range under more flexible temporal, spatial, or temperature conditions. In terms of the non-equilibrium thermodynamic properties determined by the interactions within the mesoscale of matter, contrary to the positive entropy increase of thermal effects that is proportional to useful work, the excitation and accumulation of internal energy of intermolecular interactions conducted through polarization band excitons in the polarization band electric field are positively correlated with the level of orderliness in molecular arrangement, making the production of useful work by negative entropy on the state evolution process an inherent property. Generating and controlling polarization band excitons is a general method for developing and utilizing the internal energy of molecular structures. It can not only be used for the generation of plasma states but also for the formation of other special states of matter, such as those containing only a large number of metastable and excited state particles rather than free electrons and ions.

Compared to traditional plasma generation methods based on free electrons or molecular thermal effects, the NPMEMS technology essentially aims to construct a micro-nano system platform capable of exciting, controlling, and utilizing high-flux polarization band excitons, instead of heating free electrons or releasing field emission electrons through enhancing the local field intensity in the vicinity of the nanoscale electrodes[20-25]. This technology exerts its effectiveness in controlling energy conversion modes at the mesoscale level of particle collisions, thereby establishing a negative entropy stage during plasma or other state transitions to converge the phase change process into a low-entropy thermodynamic state that can be efficiently maintained or controlled. The negative entropy stage during the general phase change process of plasma formation constitutes the core specificity of the polarization band effect plasma generation process. After the formation of the plasma state, it also fundamentally influences the non-equilibrium thermodynamic relaxation modes of plasma constituent particles across various degrees of freedom, subsequently affecting numerous crucial physicochemical properties of the plasma in electromagnetic, chemical, and gas dynamic contexts: 1) Electromagnetically, the electromagnetic properties of plasma arise from the coupling of the excited radiation field and incident field of dipoles composed of free electrons and ions under the action of external electromagnetic forces. The presence and strength of various electromagnetic wave transmission effects can be attributed to the spatiotemporal distribution characteristics of the real and imaginary parts of the complex permittivity. The real part is primarily determined by electron density. In contrast, the imaginary part is primarily determined by the collision relaxation processes in the interaction between electrons and gas molecules, charged or uncharged, thus depending on electron temperature and the energy state of gas molecules. 2) Chemically, the chemical properties of plasma are determined by the energy states of gas molecules in plasma across various degrees of freedom. From the perspective of physical kinetics and thermodynamics, they are further determined by the energy relaxation process of the components that are most active in converting external energy and possess the highest collision frequency with various particles. In terms of gas dynamics, according to the standard model of elementary particle physics, the relative strength of electromagnetic force is 36 orders of magnitude higher than that of the gravitational and only 2 orders of magnitude lower than that of the strong interactions[26]. 3) The energy of an aircraft's flow field originates from the inertia of the fluid itself, while fluid properties such as viscosity arise from electromagnetic interactions between gas molecules[27-29]. By ingeniously designing the electromagnetic field spatial distribution at the microscale to influence the mode of electromagnetic force's action on mesoscale processes, fundamental impacts can be exerted on macroscale functional features. If combined with the coupling structural design of aircraft for complementary utilization, it can also be used to modify the boundary layer structure of hypersonic flow fields, achieving important aerodynamic functions, such as the efficient drag reduction. In summary, the NPMEMS devices regulate and construct the critical conditions for negative entropy links during non-equilibrium thermodynamic processes through the design of micro-nano structures to control the spatial distribution of electromagnetic fields inducing the polarization band effect. This field effect is functioned at the mesoscale level during the energy relaxation among particles, bridging the gap between the governing processes of the micro and macro scales, to improve the efficiency and controllability of generating and maintaining plasma states. This creates a new pathway for leveraging the specificity of electromagnetic interactions with 'minimal effort yielding maximal results'.

2 Routes in initiation and development

The initiation and development of the NPMEMS science and technology have undergone nearly two decades, starting from the observation of charge separation and electron accumulation phenomena under low-potential conditions less than the ionization energy within the micro-nano scale. Through a combination of theoretical and experimental exploration, the physical mechanism of the structural effect of micro-nano scale, i.e., the polarization band effect, for efficient plasma generation has been mathematically described in theory. Based on the experimental verification of the theoretical conditions for the key effect, innovative micro-nano manufacturing technology has been employed to realize the device implementation of this mechanism. Furthermore, through the deployment of inter-locking electric transmission and field excitation technology into NPMEMS device arrays, highly controllable plasmas can be generated, enabling the functionalization of NPMEMS in specific application areas.

In fundamental research, theoretical descriptions and experimental characterizations have been systematically conducted on the generation methods of polarization band electric fields, their fundamental field-induced effects, and physical consequences within plasmas. Leveraging the accumulation of the National Key Laboratory of Advanced Micro and Nano Manufacture Technology in thick film technology, efforts have been made to simultaneously develop basic processes for sample preparation and experimental research, as well as the mathematical and physical models for theoretical purposes. Phenomena specific to the field-induced polarization band effect, such as the radial uniformity of plasma development, ultra-long time-span of the dielectric barrier discharge with positive feedback accumulation of direct field effect, sub-ionization potential energy low-voltage macro-scale ionization, and low-power cross-state phase transitions, have been discovered. The fundamental theoretical models for the generation process of polarization band effect plasma has been proposed, enabling the mathematical description and experimental verification of the basic physical mechanisms.

In applied fundamental research, to simulate and emulate the evolution process of polarization band effect plasma for the optimization of NPMEMS device micro-nano structures and controlled excitation modes, computational methods and basic software for the quasi-particle kinetic model of the polarization band excitons have been developed. An 'inert background vacuum model' has been proposed, and the software based on fluid and particle-in-cell architectures for simulating the evolution process of the polarization band effect plasmas has been developed. For the applications related to the regulation of flight vehicle flow fields and their electromagnetic scattering properties, specific software for calculating the electromagnetic scattering characteristics of polarization band effect plasma has been developed, and efforts are ongoing to develop software for simulating the evolution process and thermodynamic properties of the polarization band effect plasma in supersonic high-speed flow fields.

In applied research, addressing the challenges of developing integrated manufacturing processes for the NPMEMS plasma source chips for the aerospace applications, specialized automated micro/nano process equipment, namely, DDS, was developed in 2009. Since 2013, the integration of machine learning techniques, process automation technology, and multi-physics field computation technology in the reaction and deposition process has led to the development of an intelligent process optimization equipment, namely, KQS. This has resulted in the breakthroughs in the core processes of NPMEMS chip integrated manufacturing, forming a relatively complete micro-nano manufacturing system for the core functional structures. To meet the technological requirements of generating and controlling plasma coatings on surfaces, the methods for the cross-scaled electric transmission and the coupled excitation of the intra-chip and the inter-chip polarization band effects have been developed, and routes of the miniaturization techniques for the excitation system has been developed and verified. Research efforts aimed at complex and extreme aerospace conditions have simultaneously driven technological advancements in other application directions.

3 Application key areas

The application of NPMEMS is primarily categorized into three types: device-level applications, system-level applications, and composite applications. This classification way distinguishes the application methodology of NPMEMS devices from both a system perspective and a process perspective. When the function of the NPMEMS devices within an application system constitutes a physical process coupling relationship with other components or sections, it is considered a composite application. If their application poses constraints on other components or sections, or vice versa, it falls under the category of system-level applications. Conversely, if there is neither a physical process coupling relationship nor constraints between subsystems, it is classified as a device-level application. In the fields of electromagnetic property modulation, drag reduction, biosafety, energy security, and food security, the key technological effectiveness of the NPMEMS has been verified through the development of the prototype devices and equipment samples, and has been tested and validated by third-party institutions such as relevant entrepreneur's research institutes and the Shanghai Institute of Metrology, gaining the attention of the relevant application organizations.

The research on the NPMEMS applications has identified four key breakthrough directions for near-term focus: the aerodynamic drag reduction and heat dissipation, electromagnetic property modulation; the nuclear, biological, and chemical detection and neutralization, and the space charge detection. In our primary application areas of drag reduction and heat dissipation, as well as electromagnetic property modulation, collaborative efforts have been ongoing with the equipment system design and integration institutions for years to conduct the applied fundamental research. Given the urgency and practicality of these applications, specific requirements have been identified based on demand traction and technological characteristics, with a primary focus on efficient modulation of aerodynamic force, heat, and electromagnetic properties in the flow fields of various mobile platforms.

In the area of nuclear, biological, and chemical detection and neutralization, there are two primary research directions. Firstly, to achieve green and consumable-free plasma decontamination and sterilization of air and surfaces contaminated with biochemical warfare agents, it is urgent to address issues such as the high heat generation rate and the instability caused by strong field intensity, the high gaseous temperature, and the tendency for energy to be concentrated in a small range. Researches are being conducted on the NPMEMS plasma decontamination and sterilization technologies based on the polarization band effect to regulate and excite molecular internal energy, aiming to alter the dominant dependence of the ionization frequency on the high-energy state of free electrons, resulting in a green and efficient plasma disinfection and protection system. Secondly, to achieve online detection, inspection, and probing of chemical warfare agents with complex and abrupt variations in both composition and concentration of the agent-attacked zones, and to enhance the integration level of detection, prevention, and neutralization, it is urgent to solve the challenge of miniaturizing broad-spectrum analytical gas detectors. Researches are being conducted on the NPMEMS detection technologies that utilize the polarization band effect to selectively regulate molecular energy states, potentially leading to the development of high-selectivity micro-nano gas detectors, ultrafast chromatographic separators, and high-efficiency soft ionization sources.

In the area of space charge detection, based on the remote sensing mechanism of the polarization band effect in the electrodynamic process of space charges, the spatial mapping relationship between the radiation electromagnetic field spatial distribution pattern and the induced charge distribution pattern is constructed by utilizing the temporal signal readout electronics in the chip-size hardware mapping topology of the NPMEMS induced charge distribution pattern. This ultimately restores the mapping relationship between the space charge distribution pattern and the radiation electromagnetic field distribution pattern, enabling the long-range detection and identification of faint targets in the aerospace context. The system configuration features a low profile, low power consumption, light payload, and high integration, potentially leading to the development of an efficient and intelligent composite NPMEMS application system that combines the scatter characteristic suppression with long-range target detection functions.

To enable the application of the NPMEMS in the aforementioned fields, our current research focus is on integrating key processes, forming chip-level integrated manufacturing capabilities and specific platforms, and developing device-level and system-level capabilities tailored to the new applications.

4 Perspectives in NPMEMS research experience

The ultimate object of NPMEMS application research is to solve the plasma application problems of the physical mechanism nature that are difficult to be addressed by traditional technological routes, to improve the technological readiness level of various NPMEMS devices and systems in different application areas, and provide new methodology, new devices, and new functional systems to solve the technological bottlenecks in the selected areas. We have three main perspectives of our work experiences shared herewith: firstly, we should attach great importance to basic research, applied basic research, and sufficient experimental verification works at all stages for an original technology development with significant difficulties. Once these works are done well, the applied research and technological development will have a solid foundation. Solid basic works also give us great strength and firm confidence to tackle challenging problems. For those important demand directions where NPMEMS can solve bottleneck problems at the level of fundamental science without a definite engineering solution, we should be brave enough to make innovative breakthroughs even if the technology is relatively difficult to achieve and risky. Secondly, we need a dedicated micro-nano processing platform to ensure the development of the devices with the special structure architecture and the integration strategy. The NPMEMS devices are the micro-platforms for the polarization band effect functioning and the core hardware basis for realizing various applications. Due to the inherent complexity of their functional materials and micro-nano electrode array structures, the device manufacturing needs to be realized through the integration of a series of micro-nano manufacturing processes and the combination of multiple independent non-standard equipment. Establishing a dedicated process-integrated micro-nano manufacturing platform is conducive to controlling the quality of all process links of the whole process, improving the qualification rate, and ensuring the demand for applied research with proper batch size. Transitioning from a single breakthrough in the core structure to an integrated breakthrough in process integration, and solidifying the process line as the core process segment, is the main threshold that the NPMEMS technology needs to cross from the basic research and applied basic research to the application engineering research. We should make great efforts to improve the technological readiness level with the spirit of 'sharpening the axe should not delay cutting wood'; and develop and produce high-quality devices that meet the actual use requirements. Thirdly, we need to cultivate a team that is 'brave to tackle difficult and crucial problems' in the practice of scientific research and technological development. Under limited or even scarce objective conditions, the team can still concentrate everyone's wisdom to organize and tackle key problems, and efficiently iterate to break through the scientific and technological problems in scientific research and technological development. The application of technological innovation and innovation achievements will not be smooth sailing, and opportunities and challenges will coexist. People who persevere and grow under such conditions usually have a high sense of responsibility for the specialities and tasks they undertake, can maintain a sense of urgency and missionary in difficult environments, always learn scientifically and objectively by combining theory with practice, and continuously improve their work abilities, which is a precious force for realizing the engineering application of NPMEMS.

5 Inspirations for Micro/Nano community

After nearly two decades of scientific and applied technological research starting from theoretical hypotheses, NPMEMS has deepened our understanding of certain regularities through practice. Four key insights have emerged from this process:

Firstly, discovering and leveraging the specificity of structural effects within the micro-nano scale to construct negative entropy links in a functioning or transitioning process is crucial for developing efficient plasma generators and a significant pathway for advancing high-performance micro-nano systems. From a thermodynamic perspective, the structural effects generated by micro-nano electrode arrays enhance the efficiency of atoms and molecules in their internal structures to capture external energy and undergo stimulated transitions, reducing the energy flux density required to produce and maintain a plasma state. This effect is equivalent to an endogenous source of effective energy, manifesting as a negative entropy segment in the operation of NPMEMS. Extending this concept, the target performance of any micro-nano system is inevitably associated with a target thermodynamic state. The essential feature of achieving high performance lies in efficiently utilizing external energy to generate and maintain the thermodynamic state required for the underlying operation of the system. Therefore, establishing a general theoretical relationship between structural effects and negative entropy generation processes, consciously considering the thermodynamic essence of enhancing micro-nano system performance through micro-nano structural design, and establishing an intrinsic link between efficiency and performance, holds universal significance for the innovative development of micro-nano system technologies. Entropy is an extensive quantity, and the entropy of a system is composed of the entropy of its subsystems, integrating various superposition and coupling relationships of the entropy generation links of the subsystems based on the target thermodynamic state requirements of the whole system holds significant practical implications for the innovative development of composite high-efficiency micro-nano systems.

Secondly, the polarization band effect is a physical effect that can only be excited and formed through the combination of micrometer- and nanometer-scale functional structures. Its electric field distribution is generated through the cross-scale superposition of micro-nano artificial structures. Physical effects that operate solely at the nanometer-scale or the micrometer-scale cannot achieve this. This is due to the nature of the plasma state, which is determined by the microscopically quantized behavior of constituent particles and simultaneously by the interactions and macroscopic statistical behaviors of a large number of such microscopic systems at the characteristic scales of physical kinetics and thermodynamics. The mode of action of the polarization band electric field on gas molecules must strictly adhere to the laws of these physical processes to enable the construction of a negative entropy flow underlying the energy transfer and transformation mechanism. Therefore, it is necessary to form rigorous theoretical design methods and micro-nano integration processes based on the specific laws governing the system operation.

Thirdly, the device technology of the micro-nano structural effects faces the challenges posed by the extreme complexity of micro-nano structural microscopy, materials, and process flows, which are concentrated in the processing technology of micro-nano integrated functional structures. There are two major difficulties: first, the strong cross-scale characteristics lead to difficulties in evaluating process quality; second, the high sensitivity of the process system leads to difficulties in the manufacturing process control. To address these issues, it is necessary to establish a methodology framework for process system identification that reflects the integrity of the process and structural characteristics. It is also essential to find the intrinsic correlation between process equipment and the multi-disciplined parameter space rooted in the process physical fields and chemical reactions, and integrate computational physics technology, artificial intelligence technology, and automation technology to form a new approach for 'process-mechanism-aware' micro-nano process research and development. The main characteristics of this research and development route, which organically combines physics methods and data-driven methods, are as follows: First, it can autonomously summarize the regular connections between the spatial distribution and time-varying characteristics of physicochemical feature quantities and process output indicators during the process; second, it can enhance the validity and reliability of identifying process parameter systems and optimizing process flows based on small-sample multi-channel automated process experimentation technology; third, it can cross-scale and chip-to-wafer evaluate process-output-indicators using machine learning technology and simultaneously output optimization results for the physical and chemical fields of the process. This innovative micro-nano process technology approach significantly improves the research, development, and production readiness levels of the NPMEMS processing system and lays a new technological foundation for the development of other kinds of novel micro-nano devices.

Fourthly, plasma generation in the polarization band electric field does not simply occur by using nanomaterials with arbitrary structural features as electrodes. In our experiments, we have found that the mere introduction of nanostructures as electrodes does not always increase efficiency; it may even significantly intensify the thermal effects and result in strong thermal instability of the plasma[30]. Therefore, it is necessary to discover and utilize the physical conditions for the special macroscopic thermodynamic effects and states produced by the energy regulation processes at the micro- and meso-scales. Only by combining micro- and nano-technologies, through rigorous theoretical design and processing techniques, can we approach the formation of an efficient plasma process excited and maintained by the physical mechanism of the polarization band effect. The specific action of the polarization band electric field on the quantized bound electrons at the microscale stimulates the kinetic specificity of the energy relaxation process between particles at the mesoscale. This mesoscale specificity, under specific conditions, couples with external electromagnetic force fields, generating macroscopic impacts and manifesting as the specificity of thermodynamic states or their evolution processes.

Practices of science and engineering have shown that one cannot bypass the inherent laws and 'force' a system to generate negative entropy links during the process of generating or maintaining a certain target thermodynamic state through external forces. Instead, we must identify and utilize the special inherent properties of the system, at the micro- and meso-scales, to form an internal tuning mechanism for the accumulation of internal energy and macroscopic ordering, making negative entropy link a spontaneous tendency of the thermodynamic state transition and maintenance of the system operation dynamics in a condition of constant external disturbances. The combination of theoretical and experimental practices to utilize micro- and nano-structural effects is an effective approach to finding such special conditions. Micro- and nano-technologies should consider how to regulate not only the microscopic systems with significant quantized features but also the transition of this regulatory effect to the macroscale. Relying solely on the modification of an extremely limited number of microscopic systems is often insufficient. In many cases, it is also necessary to simultaneously modify the interaction mechanisms between a sufficiently large number of microscopic systems to truly achieve a spontaneous steady state in the scale of thermodynamic laws functioning for efficient control and technological applications of a quantized featured system. This is the task and challenge we face.

Author Contributions:

The authors jointly conducted the crucial aspects of this work, including conceptualization, methodology, formal analysis, and writing-original draft. Zhongyu Hou has conducted data curation, investigation, resources, and project administration. Henggao Ding has conducted supervision, validation.

Funding Information:

This work was financially supported by the National Natural Science Foundation of China (60906053, 612040 69, 61274118, 61306144, 61504079, and 11605112), Scientific and Innovative Action Plan of Shanghai (15DZ1160800 and 17XD1702400), and National Key Research & Development (R&D) Program of China (Grant No. SQ2023YFC2600062).

Data Availability:

The authors declare that the main data supporting the findings of this study are available within the paper and its Supplementary Information files.

Conflict of Interest:

The authors declare no competing interests.

Dates:

Received 13 June 2024; Accepted 25 June 2024; Published online 30 June 2024

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