# Dynamic Synchronisation Process of Ion Implantation and Rapid Thermal Treatment

Kehan Zhu

Detroit Green Technology Institute, Hubei University of Technology, Wuhan, 430068, China

frank_zhu0532@163.com

**Abstract.** With the rapid development of semiconductor manufacturing technology, the construction of device structures and gradual reduction in dimensions make the more heightened demands on doping depth control and activation efficiency. Therefore, in order to decrease lattice damage, enhance the activation efficiency, and reduce thermal budget at the same time during ion implantation and annealing processes, this paper lists four dynamic synchronisation process pathways, breaking the traditional method, which is called "implant first, anneal later". Each approach applies different methods and technical equipment, which enable tailored process routes in different scenarios. These methods include: plasma implantation, which has the advantageous conditions for large-area uniform implantation; With the specialty of regional and precision control, called synchronous laser scanning annealing; the significant use of laser and flash lamp assistance in ultra-shallow junctions; and the common process and industrial scalability provided by integrated high-temperature hot plates. These four approaches offer new perspectives for semiconductor manufacturing, while providing foundational concepts for future industrial-scale production and experimental precision fabrication. They improve semiconductor processes to lower power consumption, enable more complex structures, and provide finer controlt.

**Keywords:** Semiconductor process; Ion implantation; Annealing process; Rapid thermal processing.

## 1. Introduction

During these years, the progress of integrated circuits and semiconductor manufacturing has required highly efficient and precise doping for escalating demands. As a crucial process, ion implantation inherently generates significant lattice dislocations and vacancies because of unbalanced and high-collision nature. The annealing after that is important to repair the lattice structure and activate dopant atoms. Besides, the recent application of 3D structured devices and high-power devices imposes strict requirements on doping depth and junction formation. As a result, the traditional "injection with global annealing later" process flow has displayed significant limitations.

Although conventional rapid thermal annealing (RTA) processes achieve lattice repair in seconds, high-temperature diffusion in shallow junction structures can cause deeper junction depth and disrupt channel characteristics. Complex device construction, such as FinFET transistors [1], trench-type power devices, and CMOS structures, has regional inhomogeneities in ion implantation and annealing, as well as varying degrees of activation.

The objective of this study is to explore synchronized processes integrating dynamic ion implantation with annealing. It proposes an innovative approach to overcome the limitations of the traditional concept of "injection with global annealing later". The research employs plasma-assisted ion implantation (PII) [2], in-situ thermal sources (remote infrared heating, laser heating), and transient heat sources (laser, flash lamp)and so on to elevate lattice temperature for repair. As for complex structures such as three-dimensional architectures, it enhances doping uniformity and high activation, and also improves the industrial window and consistency of the structured devices.

# 2. Theoretical Analysis

## 2.1. Plasma Immersion Ion Implantation

Plasma is a high-energy state of matter formed when a gas undergoes ionization under intensive electric fields, which requires specific experimental conditions for generation [2]. Based on plasma, ion implantation (PII), leveraging these properties, constitutes a significant surface modification technology. Through applying a negative pulsed bias to the sample, the positive ions within the plasma bombard the material surface under electric field acceleration, then form an ion sheath layer. This alters the surface composition and structure, enabling efficient functional regulation [1].

## 2.2. Rapid Thermal Processing Technology

Rapid thermal processing (RTP) is a technology that involves heating wafers to temperatures ranging from 200 to 1700°C in seconds before rapid cooling, with heating rates that can reach 20°C/s to 250°C/s [3]. Its central advantage is shortening the duration of sustained high-temperature annealing, so that it can reduce impurity diffusion and annealing side effects. This ensures device precision, lowers thermal budgets, and induces repairs of lattice damage. The technology of RTP shows extensive application in industrial scenarios such as doping activation, thin-film annealing, and surface oxidation. Current implementation methods mainly use pulsed or continuous lasers and electron beams, ion beams, and broadband light sources and other technical approaches.

# 3. Analysis of Rapid Thermal Processing Methods

## 3.1. Far-Infrared Heating

### 3.1.1 Theory of Infrared Thermal Radiation

Radiation is the phenomenon of energy transfer via electromagnetic waves. The electromagnetic spectrum spans wavelengths from approximately 0.1μm to 100μm.These rays are called thermal radiation. They originate from lattice vibrations within solids or the migration of bound electrons, and their propagation are defined as thermal radiation. At the red end of the visible spectrum, radiation with wavelengths ranging from approximately 0.76μm to 100μm is defined as infrared radiation [4]. Long-wave infrared radiation, or far-infrared radiation, is infrared radiation with wavelengths over 4μm in vacuum. Medium-wave infrared radiation, or medium-infrared radiation, refers to infrared radiation with wavelengths greater than 2μm but less than 4μm in vacuum. Short-wave infrared radiation, or near-infrared radiation, is radiation with wavelengths below 2μm in vacuum.

### 3.1.2 Far-Infrared Heating Technology

The 4–14 μm wavelength band is commonly designated as far infrared in industrial processes. Far infrared heating doesn’t require preheating the air. Nevertheless, radiation heats the object's surface directly without the need for a medium to conduct heat. As a result, it avoids the potential issue of surface overheating with insufficient internal temperatures that can occur in traditional heating ways. It has the characteristics of the ability to achieve uniform temperatures across all parts of the heated object, as well as enhancing heating quality[5]. Moreover, its advantages of rapid heating response and excellent directionality prove high benefits for industrial processes requiring local heating and rapid temperature elevation.

## 3.2. Laser Heating

### 3.2.1 Principles of Laser Annealing

The thermal interaction between laser radiation and matter is the absorption of light energy by the material. When a laser beam strikes a material's surface, a portion of the energy will be reflected and lost, while the remaining energy is absorbed and converted into thermal energy [6]. For solid materials, the absorbed photon energy is transferred to free electrons via inelastic collisions. The kinetic energy of these electrons will increase and undergo secondary collisions with the crystal lattice, and then convert energy into thermal vibrations within the lattice. This process causes the material's temperature to rise dramatically within a short time.

### 3.2.2 Laser Annealing Systems

Laser annealing technology is a process that uses high-energy-density pulsed lasers to irradiate materials, causing them to absorb heat and undergo molecular reorganization. A typical laser annealing system comprises three main parts: the laser source, the optical shaping system, and the sample stage, as illustrated in Figure 1.

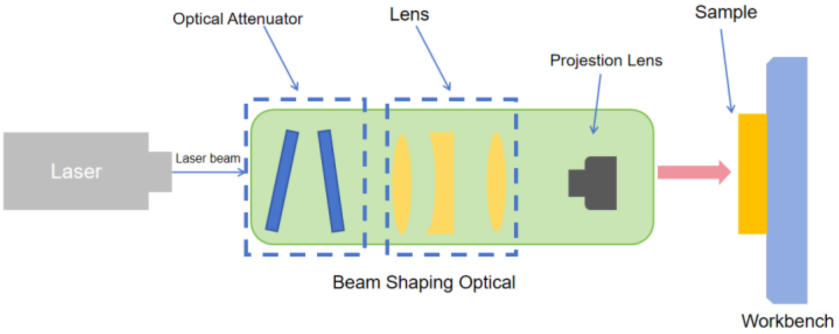

**Figure. 1** Schematic diagram of a laser annealing system

According to the working medium, laser devices can be categorized as solid-state lasers, liquid-fuel lasers, semiconductor lasers, and excimer lasers. Among them, excimer lasers possess substantial pulse energy and peak laser power. Therefore, this laser technology has extensive application in scientific research and industrial sectors such as solar cells, display panels, and semiconductors.

## 4. Analysis and Comparison of Methods and Processes for Achieving Synchronized Processing

### 4.1. Dual-Head Scanning Injection and Localized Heating

### 4.1.1 Equipment and Design

The dual-head scanning method integrates an ion implantation head with a local heating head for coordinating operation. It uses beam scanning techniques such as the multifunctional femtosecond laser amplifier (DLIP) to identify and segment material patterns for sequential implantation [7]. Immediate transient heating follows implantation to realize local lattice repair and activation. The implantation head comprises an ion source, accelerator, and dose scanning control structures (electromagnetic scanning, rotary stage, Faraday cup array). The heating head consists of a microbeam laser (nanometre-scale) and a laser energy meter to achieve dual-head collaborative operation on a shared platform.

### 4.1.2 Dose Scanning Control

The dose control precisely measures ion quantities and regulates ion movement within this process. When integrated with electromagnetic scanning, it could further enable waveform scanning data storage and output, and enhance beam current and dose control precision.

The system architecture comprises the components, which are illustrated in Figure 2. The dose integrator serves as the control hub to drive motors and collect beam current. The scanning power supply receives signals from the dose integrator and generates the scanning electric field [8].

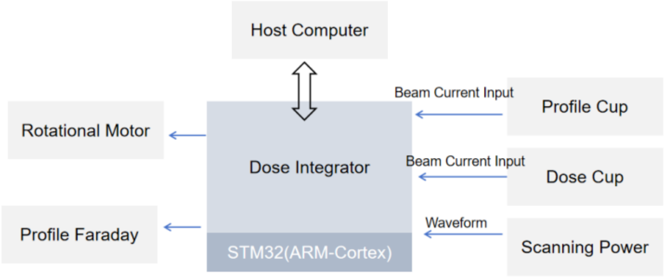

**Figure. 2** Dose Control System Architecture

For the scanning of the dose controller, the ion beam moves the Faraday cup horizontally to measure the beam current value at each point[9]. Using a horizontal scanning waveform generator, it continuously calibrates and corrects the voltage slope values obtained from scanning each point based on the horizontal distribution of the beam current. After obtaining the voltage waveform results, adjustments are made.

The implantation process is accomplished through horizontal and vertical beam scanning. For each vertical mechanical scan increment of ΔS, four horizontal reciprocating scans are completed to acquire the dose Q. The single-pass ion density is denoted as D, satisfying the equation $D = Q \div (\Delta S \times W)$, where W represents the aperture width of the Faraday cup [10].

### 4.1.3 Process Flow

The fundamental cycle of dual-head scanning implantation with localised heating involves the ion implantation head performing scanning implantation, followed by localised heating via femtosecond short-pulse laser heating with minimal delay. After a cooling interval, the next fundamental cycle commences [11]. This process employs serpentine scanning with synchronised laser tracking, incorporating cooling intervals at the start and end of the path. Priority is given to heat-sensitive areas such as small metal components and thin films for treatment. The entire material employs a uniform heating scanning core, with interleaved processing across the material to balance internal thermal distribution.

Spatial and temporal calibration employs multi-point etching targets and laser positioning for spatial alignment, with trigger criteria established to minimise temporal deviation. Temperature control prevents high-temperature melting through laser reflection feedback, regulating transient thresholds to govern operational start/stop behavior.

### 4.1.4 Process Characteristics

Employing a method of regional scanning injection, each small injected area undergoes local heating followed by instantaneous annealing using laser microbeams or microwave sources. Its significant characteristics are exceptional spatial selectivity and high resolution, which enable precise control over local doping depth and concentration. The laser amplifier's beam pattern recognition demonstrates strong adaptability for intricate structural scenarios. But the system is complex, coupled with demands for precision synchronisation and nanometre-level positioning,and imposes stringent requirements on equipment.

## 4.2. Synchronised Laser/Flash Lamp-Assisted Annealing

### 4.2.1 Equipment and Systems

Considering ion implantation, any ion implanter or PII system may be employed. Regarding light source assistance, short-pulse laser annealing (e.g.excimer lasers) may be used according to specific industrial requirements. When integrated with computer systems, this enables local, short-duration peak-temperature annealing with precise regional control, which makes it suitable for ultra-shallow junctions and micro-area processing in devices such as CMOS and FinFET. Alternatively, flash lamp annealing (FLA) systems may be employed as light sources, facilitating larger-area coverage and suitability for high-throughput, bulk processing scenarios with less stringent precision requirements.

### 4.2.2 Process Flow

The integral concept of synchronous laser annealing involves applying short-duration, high-temperature peak processing to local or entire regions during ion implantation or within an extremely brief delay post-implantation. This is realized by using laser pulse generators or flash lamps, simultaneously activating dopants and repairing defects. The approach offers high efficiency within a short time and high activation capability.

For time control, a Field Programmable Gate Array (FPGA) forms the foundation, using the Precision Time Protocol (PTP) and SM4 encryption algorithm to achieve synchronised timing control[12]. During process execution, dual-wave infrared thermometry captures peak temperatures and compares them against target values, enabling detection and regulation of the light source system's energy output.

### 4.2.3 Process Characteristics

The synchronised process employs a short-pulse laser and flash annealing to achieve instantaneous local heating of the wafer via a short-delay light source, concurrently with ion implantation. Techniques such as microsecond ultraviolet laser (UV-LA) and plasma resonance (SPR) generated in synergy with the PII system further suppress implantation damage [13], which can make high activation rates and ultra-shallow junction requirements. Its advantages in high temporal resolution and extremely short thermal diffusion making it suitable for low thermal budget and ultra-shallow junction processes. But laser uniformity and local thermal stress require precise control.

## 4.3. Combining Plasma Injection with External Heat Sources

### 4.3.1 System Architecture

The primary architecture of the PII system comprises a chamber, ion source, gas source, vacuum apparatus, and pulsed bias device (Figure 3). Process gases for implantation may include $PH_3$, $AsH_3$, $B_2H_6$, etc., for different doping.

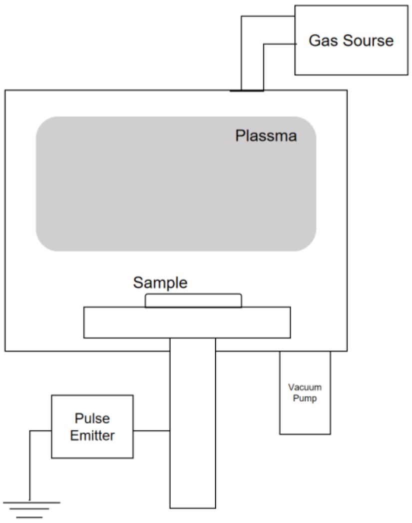

**Figure. 3** Schematic diagram of the PII system

For heating, a combination of plasma self-heating and external auxiliary heating is employed. External heat sources may utilise infrared radiation or resistance heating. The sample carrier stage incorporates ±15° rotational oscillation to ensure uniform injection across multiple angles. Photoresists cannot be used in the plasma environment; consequently, masks must be implemented as hard masks (utilising $SiO_2$, $SiN_2$, etc.), maintained at a thickness of 20–60 nm.

### 4.3.2 Process Flow

The fundamental process first stabilises the plasma for approximately 10 seconds while the heating platform gradually increases in temperature.

In order to couple injection with annealing, the bias pulse is switched ON, accelerating ions within the sheath layer for injection. At the same time, heating facilitates repair. When the bias pulse is switched to OFF, ion acceleration ceases. Using the plasma's self-heating energy alongside auxiliary heating from the platform completes the subsequent activation and repair process. After pulse deactivation, a constant-temperature environment is maintained for approximately 30 seconds to achieve dynamic annealing completion.

During plasma injection, the bias voltage must be controlled to stabilize the plasma. Improving the temporal evolution of the plasma boundary layer by increasing the current density parallel to the wall, appropriately extending the bias rise time, and introducing neutral gas pressure [14]. This enhances efficiency and ensures high-performance stability.

### 4.3.3 Process Characteristics

The combined plasma injection and external heating approach utilizes plasma both as an ion implantation source and as a wafer heating mechanism, enabling simultaneous implantation and annealing. The main characteristic is the suitability for complex three-dimensional structures (such as trenches and FinFET devices), facilitating large-area doping while maintaining uniformity. Plasma instability during the process complicates temperature control. Adjusting the boundary layer formation through bias voltage control reduces defects caused by unstable collisions of plasma near the chamber periphery.

## 4.4. High-Temperature Table Annealing

### 4.4.1 Equipment and Systems

Ion implantation utilizes existing ion implanters or employs mass-selective magnetic fields to accelerate ions emitted from the ion source.

The heating system uses an in-situ heating source primarily, with the use of far-infrared radiation heating technology for heating and temperature regulation of the hot stage. Inert gas flow beneath the stage enhances thermal conductivity and ensures uniform temperature control.

The monitor of energy and dose employs dual-wavelength infrared thermometry, with the dose controller sampling beam waveforms to regulate dose.

### 4.4.2 Process Flow

Under the stable conditions, the heating platform material is preheated and maintained at a constant temperature for 1 minute. Following angle calibration, injection commences while maintaining the target temperature to regulate far-infrared radiation energy. Therefore, the post-process tail temperature is kept isothermal to ensure completing activation and repair, followed by controlled cooling.

### 4.4.3 Process Characteristics

High-temperature platform annealing is heating the entire wafer during ion implantation to achieve instantaneous repair of implantation damage and activation of dopant atoms. Its remarkable features are high system integration, strong process continuity, and simplicity, which make it suitable for conventional planar devices. However, global heating may cause excessive thermal diffusion depth and result in lower precision control for shallow junction structures.

## 4.5. Comparative Analysis of Methods

As shown in Table 1, the four synchronous process approaches above outline distinct advantages, disadvantages, and technical prerequisites. Their application effectiveness varies across different industrial scenarios. When coming across diverse process conditions, the selection should be based on a comprehensive assessment of requirements and constraints.

**Table 1.** Comparison of Advantages, Disadvantages, and Applicable Scenarios for Four Implementation Methods.

| Implementation Method | Principal Advantages | Principal Drawbacks | Applicable Scenarios |
|---|---|---|---|
| Dual-head scanning injection with localised heating | Highest spatial resolution, enabling regionalised custom processing with enhanced precision | High equipment complexity, elevated cost, and stringent precision requirements | Three-dimensional components; scientific research and customised process products |
| Synchronised laser/flash lamp-assisted annealing | Rapid equipment response; suitable for ultra-shallow junction requirements | Narrow process window; demands advanced energy control techniques with potential surface melting risks | Ultra-shallow junction process; low thermal budget process |
| Plasma injection combined with external heat sources | Suitable for complex, 3D structures; good doping uniformity; excellent large-area processing capability | Equipment complexity is relatively high, with greater plasma instability | 3D embedded devices, large-wafer fabrication |
| High-temperature bench annealing | Simple process, high compatibility with equipment architecture | Limited temperature control precision, prone to excessive thermal diffusion | Conventional manufacturing process, suitable for scenarios with low requirements for shallow junctions |

## 5. Conclusion

This paper investigates dynamic synchronisation techniques for ion implantation and annealing, raising four process approaches and analysing their respective advantages and characteristics: Dual-head scanning offers spatial precision control and highly suitable for precision scientific devices; Synchronised laser/flash lamp assistance demonstrates significant advantages in ultra-shallow junction processes; Plasma PII system technology assistance is suitable for large-area uniformity and self-heating assistance; The hot stage high-temperature heating process is simple and stable, and offers greater compatibility. These approaches provide novel pathways for semiconductor manufacturing, with coordinated processes reducing thermal budget and decreasing implantation damage. Furthermore, they offer substantial impetus for future advancements in nano-precision processes, intelligent control systems, and three-dimensional integration technologies.

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