SEMICONDUCTOR FRONT-END · PART 3-10

Ion Implantation and Annealing Putting dopants in place, then making them work

A transistor needs carefully defined regions that conduct electricity in different ways. Ion implantation creates those regions by accelerating charged atoms into a wafer. The beam's charge tells us how many ions arrive; their species and energy help determine where they stop. There is a price: the impacts damage the crystal. Annealing must repair that damage and activate the dopants while keeping them close to their intended positions. This lesson connects the beamline, the atomic physics and the global equipment industry.

Semiconductor Front-End Series · Part 3, Lesson 3-10 · Level ★★★

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How to read this lesson

Reported identifies information stated in the cited source, including attributed company estimates; Calculation identifies an estimate worked out in this lesson; Outlook marks forecasts and roadmap requirements; Interpretation marks an illustrative judgement. Standard physical explanations are generally untagged. Figures are schematic and not to scale. Numbered links lead to the supporting sources.

Learning goals

- Explain what ion implantation controls, and why it displaced thermal diffusion in many doping steps.
- Connect voltage, magnetic deflection and measured beam current to ion energy, species selection and dose.
- Read a depth profile and explain projected range, straggle and channelling.
- Distinguish crystal repair from dopant activation, and explain why annealing can also spread a junction.
- Identify the main equipment categories and discuss suppliers without confusing a company claim with an independent comparison.

1. The lesson in three ideas

- **Implantation controls a population of atoms.** A mask selects the region, the integrated beam current sets the dose, and ion species, energy and crystal orientation shape the depth distribution. It does not place each atom at a chosen lattice site.
- **Getting atoms into silicon is only half the job.** Impacts disturb the crystal. Annealing repairs much of the damage and makes dopants electrically active, but can also redistribute them. Damage-related diffusion is a particular concern for shallow junctions.
- **The equipment business is concentrated but international.** A cited METI report assigns 51% of the ion implantation equipment market to Axcelis and 28% to Applied Materials. Other suppliers include companies in Japan, Taiwan and China. The report's publication year is known; the data year in its market chart is not [7] [9]. Reported

2. Why deliberately add impurities?

A tiny change in composition changes electrical behaviour

In silicon, phosphorus and arsenic act as donors, supplying electrons and producing **n-type** material. Boron acts as an acceptor, producing **p-type** material in which holes carry charge. A transistor combines such regions with insulating layers and a gate. The dopant concentration and its position affect how readily current flows and the voltage required to turn the device on.

Axcelis's 2025 annual report describes a typical manufacturing process as requiring about **20 implantation steps**, with significantly more in advanced processes. Each step specifies the dopant species, dose, energy and implant angle [7]. Reported Think of these as a recipe for an electrical region, rather than simply an instruction to add an impurity.

Why not just let dopants diffuse in from the surface?

Thermal diffusion supplies dopants at the surface and uses heat to move them into the wafer. The Semiconductor History Museum of Japan explains that surface concentration, depth and profile shape became difficult to control independently as devices required shallower junctions. It describes the transition towards implantation in the early 1980s [2]. Reported

Implantation offers several advantages: the wafer need not be heated to a diffusion temperature during the implant; dose can be monitored electrically; photoresist can define selected regions; and dose and depth can be adjusted more independently within the limits of the tool and material [1][2]. Reported This does not remove the later thermal budget: an activation anneal is still required.

The Stanford EE212 handout gives a representative dose range of **10^{11} to 10^{16} ions/cm²**, highlights accurate dose control and MOS threshold-voltage adjustment, and identifies the principal drawbacks: lattice damage, anomalous diffusion during annealing and charging of insulating layers [1]. Reported

An early idea that already included annealing

William Shockley's patent, filed on 28 October 1954 and granted on 2 April 1957, describes forming semiconductor regions by ionic bombardment. Its claims also include annealing to repair the damage caused by irradiation [6]. Reported The pairing of implantation and heat treatment was present from an early stage.



From left: John Bardeen, William Shockley and Walter Brattain. According to Wikimedia Commons, this Bell Laboratories publicity photograph dates from around the public announcement of the transistor in June 1948. Shockley filed the implantation patent six years later [6].

Image: AT&T / Wikimedia Commons / Public domain. Resized and converted to WebP.

Historical accounts describe research in the 1950s, more substantial equipment development in the late 1960s and practical use in the early 1970s [3]. Reported A Japanese industry retrospective places medium-dose production around 1972, high-dose production around 1977 and the use of high-energy implantation for deep wells in the 1990s [4]. Reported These are historical milestones in the cited accounts, rather than a claim that all manufacturers changed processes at the same time.

Japan's development programme began in 1968, with groups involving Susumu Namba at RIKEN and Hitachi, and Ito at Waseda University and Toshiba. Namba recalled objections that large ions would either fail to penetrate or destroy the crystal beyond practical use [5]. Reported The underlying engineering question remains recognisable today: how much useful doping can be achieved without leaving unacceptable damage?

3. Inside an implanter: create, select, accelerate, measure

Follow the beam

A simplified beamline has five functions [1]. Reported

1. **Create ions.** An ion source turns a gas or solid feed material into charged species and extracts a beam.
2. **Select the required species.** A magnetic analyser bends trajectories; a resolving slit admits the desired beam.
3. **Set the energy.** Electric fields accelerate the selected ions, or adjust their final implantation energy.
4. **Distribute the beam.** Beam scanning and/or wafer motion spread the implant across the required area.
5. **Measure charge.** Faraday cups and the dose-control system measure beam current so that the delivered dose can be controlled.

Axcelis describes beam energies spanning hundreds of electronvolts to **8 MeV**, and currents from microamperes to milliamperes, across its equipment applications [7]. Reported The exact beamline arrangement and measurement positions vary by tool.

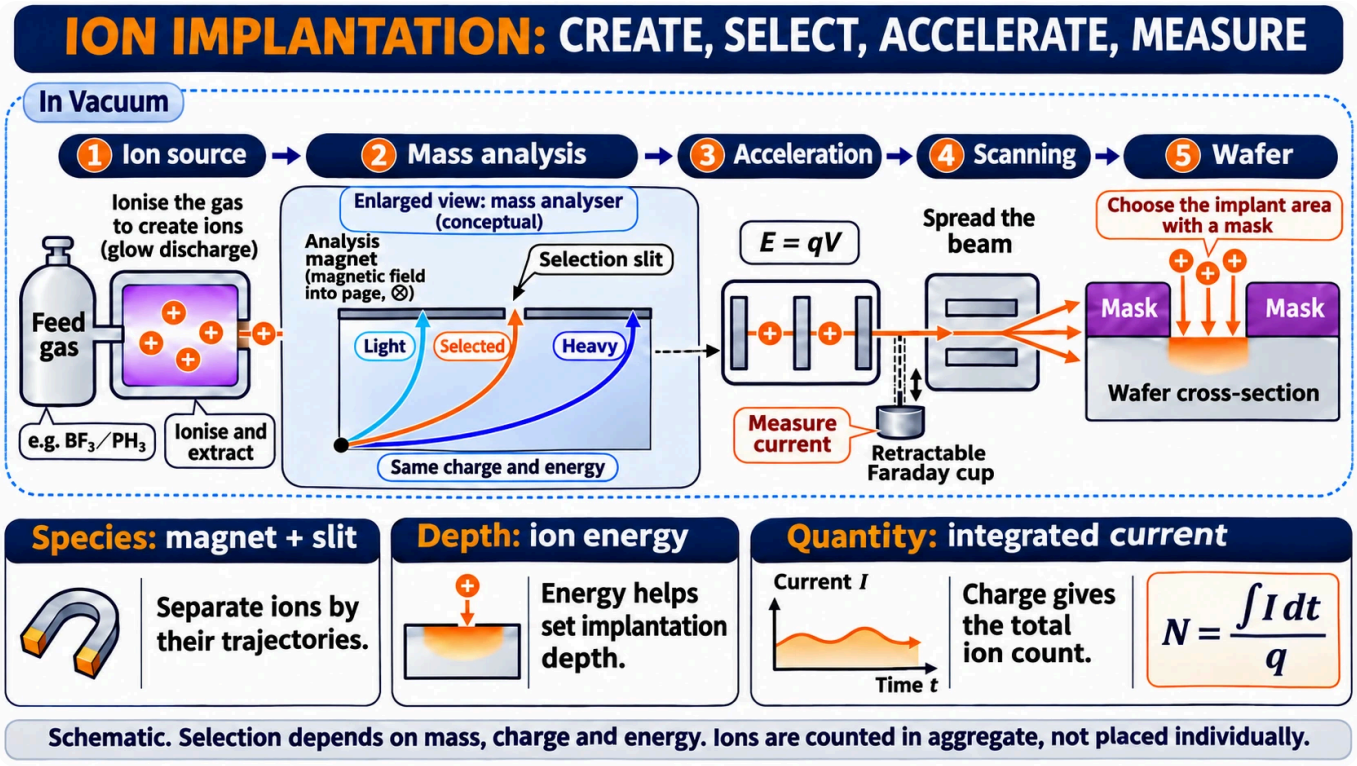


Figure 1 **From ion source to wafer** (schematic)

Reading the figure

The enlarged analyser is a conceptual inset, not the literal pipe layout. Its trajectories exaggerate the difference in curvature. The comparison assumes the same charge and kinetic energy: lighter ions then follow a smaller radius. A Faraday cup measures charge and may be inserted or withdrawn; the drawing does not imply that a cup permanently blocks the wafer beam. Real systems use different scanning, handling and dosimetry arrangements [1].



An ion implantation machine in a museum display, as identified by Wikimedia Commons. The long vacuum beamline provides a controlled path for the charged particles.
Image: Edelmauswaldgeist / Wikimedia Commons / CC0. Resized and converted to WebP.

Physics check 1: voltage sets energy; a magnet bends momentum

An ion with charge q accelerated through a potential difference V gains energy **E = qV**. A singly charged ion gains 10 keV across 10 kV; a doubly charged ion gains 20 keV across the same voltage. Nissin's cited SiC equipment report gives an example of a 320 kV acceleration voltage and triply charged ions reaching **960 keV** [11]. Reported The multiplication is 320 × 3 = 960. Calculation

Using E = ½mv² and the atomic weights in PubChem [13], the approximate speeds at 10 keV are: Calculation

Ion	Atomic weight	Speed at 10 keV
Boron B^+	10.81	420,000 m/s
Phosphorus P^+	30.97	250,000 m/s
Arsenic As^+	74.92	160,000 m/s

For motion perpendicular to a uniform magnetic field, qvB = mv²/r. Therefore **r = mv/(qB) = √(2mE)/(qB)**. At the same energy and charge, a heavier ion has a larger bend radius. A slit can therefore separate species with different trajectories.

For singly charged ions at 40 keV in a 0.5 T field, the radii are approximately 0.19 m for boron, 0.32 m for phosphorus and 0.50 m for arsenic. Even boron isotopes with mass numbers 10 and 11 differ in radius by about 5%, since √(11/10) ≈ 1.05. Calculation Magnetic analysis depends on charge and energy as well as mass.

Current becomes an ion count

Each ion carries charge q = ze, where z is the charge state and e ≈ 1.602 × 10^{-19} C. Integrating the beam current gives the collected charge. Dividing by q gives the number of ions. The historical account also describes dose measurement in terms of the time-integrated beam current [2]. Reported

Physics check 2: how long does an implant take?

For a constant current of singly charged ions delivered uniformly and entirely to area A, **Q = It/(eA)**, where Q is dose in ions/cm². This idealised calculation excludes scan losses and other practical corrections.

A 300 mm wafer has an area of about 707 cm². A dose of 10^{15} ions/cm² requires about 7.1 × 10^{17} ions, or 0.11 C. At 1 mA, that takes roughly **110 seconds**; at 10 mA, roughly **11 seconds**. A lower dose of 10^{12} ions/cm² takes about 11 seconds at 10 µA. Calculation

This explains why high-dose steps benefit from high-current tools. Historical medium-current tools operated in the microampere range, whereas high-current machines for heavily doped source/drain regions used milliamperes [2]. Reported Production dosimetry must account for beam utilisation, scanning and effects such as secondary electrons. Molecular ions also require a distinction between the number of incident ions and the number of dopant atoms they carry.

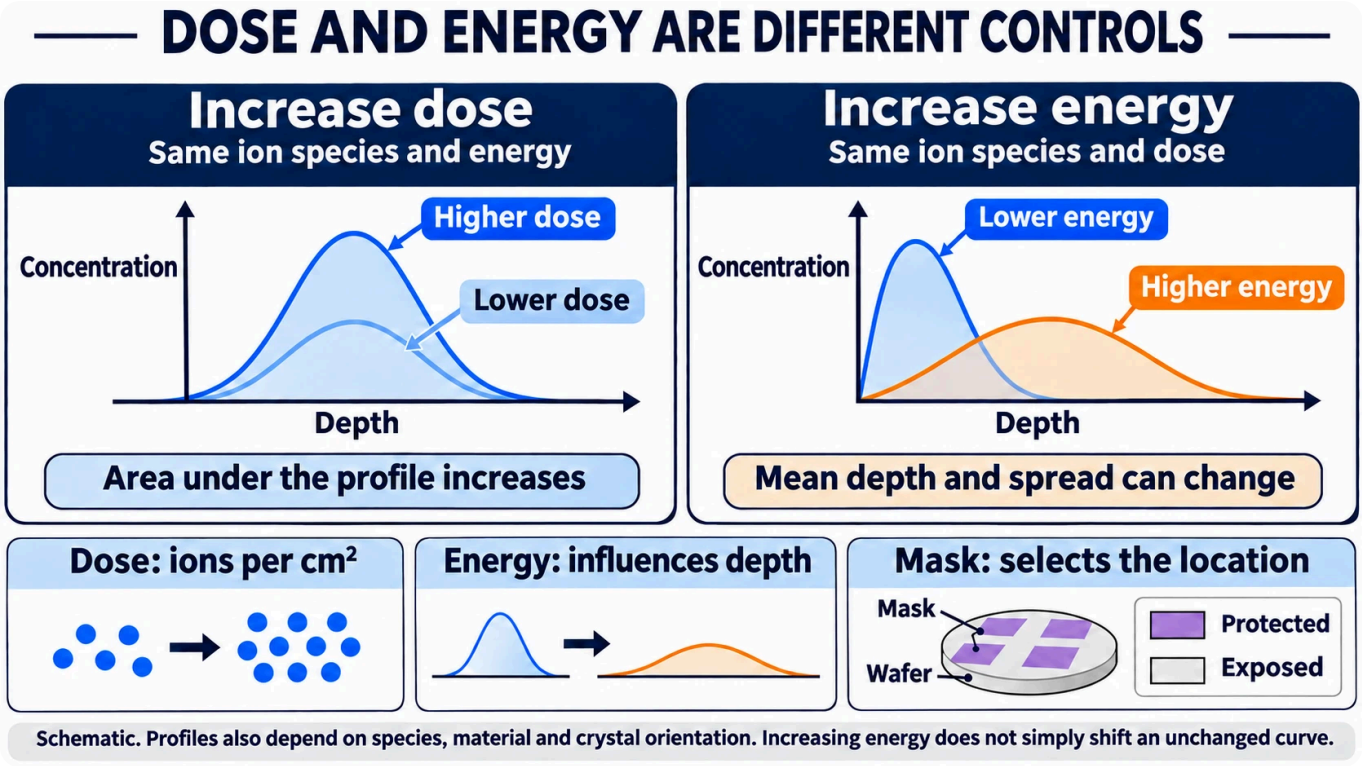


Figure 2 **Dose controls quantity; energy influences depth** (schematic)

Reading the figure

With the species and energy fixed, increasing dose increases the area under the concentration-versus-depth profile. With species and dose fixed, changing energy can change both mean depth and spread. The height of the peak is not the dose: dose is the depth integral of concentration. These are conceptual curves, not measured profiles [1].

Three broad equipment categories

Axcelis groups implanters by their dose and energy capabilities [7]. **Reported** The categories describe different process needs, rather than a simple good-better-best ranking.

Category	Typical role in the cited description
Medium-current	Moderate-to-low dose and energy ranges; historically the first category
High-current	High doses, commonly at lower energies
High-energy	Deeper implants, with higher energies and generally lower doses



An ion implantation machine at the LAAS-CNRS technology facility in Toulouse, France, as identified by Wikimedia Commons. The photograph shows the equipment front rather than the complete beamline.
Image: Guillaume Paumier / Wikimedia Commons / CC BY-SA 3.0. Resized and converted to WebP.

4. Where do the ions stop?

Two ways to lose energy

An energetic ion does not glide to a precisely chosen depth. It loses energy through **nuclear stopping**, involving collisions with atomic nuclei, and **electronic stopping**, involving interactions with electrons. The sequence of encounters differs from ion to ion [1]. Reported

Nuclear collisions deflect the incoming ion and can knock silicon atoms out of position. Electronic interactions drain kinetic energy without requiring the same direct displacement event. Their relative importance depends on ion species and energy. The cited handout gives crossover energies of roughly 17 keV for boron, 150 keV for phosphorus and above 500 keV for arsenic and antimony [1]. Reported A species cannot be assigned permanently to just one stopping mechanism.

A distribution, not a single stopping depth

The **projected range, R_p**, is the mean penetration depth measured normal to the surface. The **range straggle, ΔR_p**, describes the standard deviation of that depth distribution. A Gaussian is often a useful approximation, although real profiles can be asymmetric and have long tails [1]. Reported

For the Gaussian approximation, the peak concentration C_p and dose Q are related by $\mathbf{Q = \sqrt{(2\pi)}\,\Delta R_p\,C_p}$ [1]. Reported R_p coincides with the peak only within that approximation; its definition is the mean projected depth.

Physics check 3: a high concentration can still be a small atomic fraction

Suppose Q = 10^{15} ions/cm² and ΔR_p = 20 nm = 2 × 10^{-6} cm. Then $C_p \approx 10^{15}/(2.507 \times 2 \times 10^{-6}) \approx$ **2×10^{20} atoms/cm³**. Calculation

Using silicon's density of 2.3296 g/cm³ and atomic weight of 28.085 from PubChem [13] gives about 5.0 × 10^{22} silicon atoms/cm³. The example peak therefore corresponds to roughly **one dopant atom per 250 silicon atoms**. Calculation This is a chemical concentration calculation. It does not mean every dopant is electrically active, or that carrier concentration must equal dopant concentration.

Ions also spread sideways. The handout illustrates this with a Monte Carlo calculation of 1,000 phosphorus-ion trajectories at 35 keV. The resulting distribution is elongated along the beam direction, with some lateral spread beneath a mask edge [1]. Reported A mask must be thick enough to stop the relevant implant, taking account of range and straggle within the mask material.

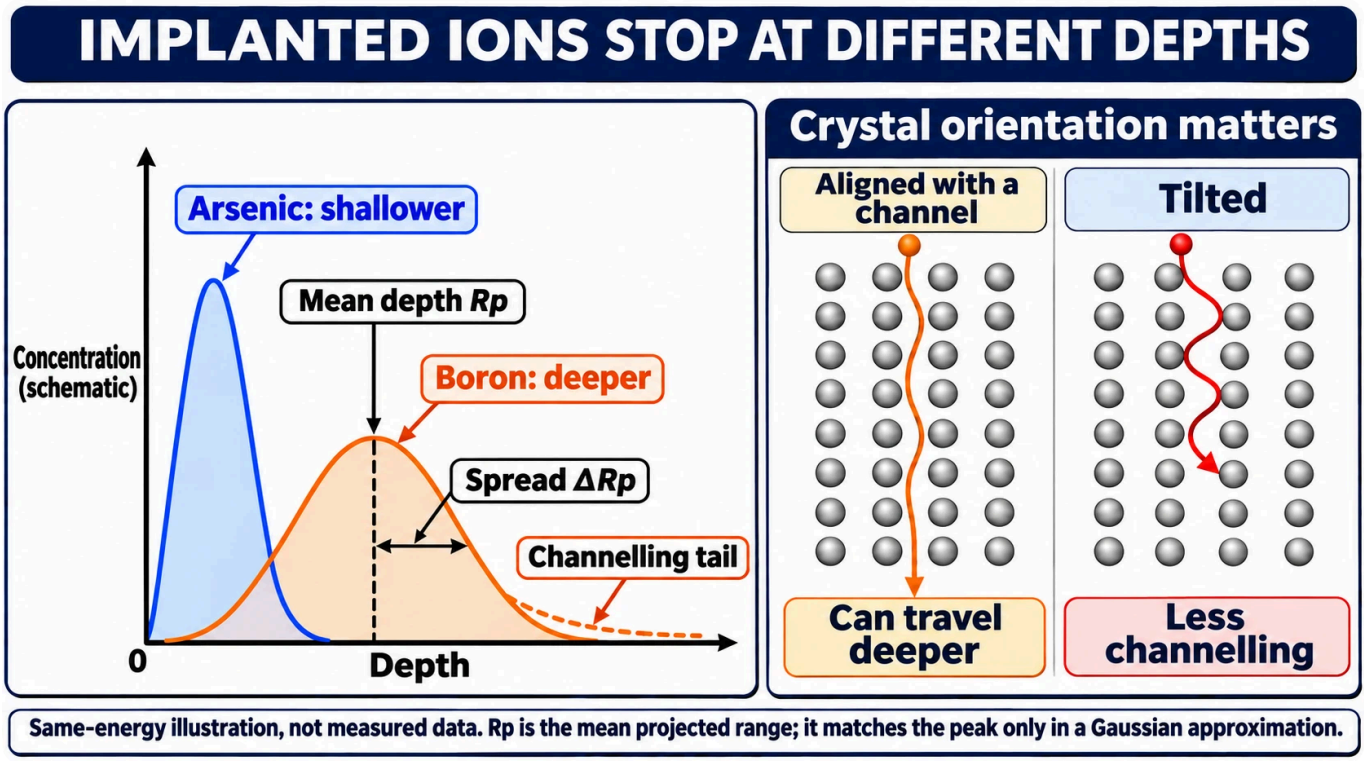


Figure 3 **Projected range, straggle and channelling** (schematic)

Reading the figure

The concentration axis is linear and schematic. ΔR_p represents one standard deviation, not the full width of the profile. The dashed tail illustrates deeper penetration caused by channelling. The lattice cartoons explain orientation qualitatively; neither the atomic geometry nor the tilt angle is drawn to scale [1].

Channelling: an open route through the crystal

A crystal contains ordered rows and planes of atoms. An ion aligned with an open direction can avoid close collisions and travel farther than a random-orientation model predicts. This is **channelling** [1]. Reported

A thin screen oxide, wafer tilt and azimuthal rotation can reduce channelling, although they do not eliminate it entirely. The handout gives **7° tilt** as a conventional example [1]. Reported It is not a universal setting: the appropriate angle depends on crystal orientation, species, energy and device geometry. Implant angle is consequently a process parameter, not an incidental alignment detail.

5. Annealing: repair the crystal and activate the dopants

One impact can disturb many atoms

The handout uses a 30 keV arsenic ion with a range of about 25 nm, or around 100 atomic planes, to illustrate damage. Its simple displacement estimate is $n \approx E/(2E_d) = 30{,}000/(2 \times 15) \approx$ **1,000 displaced atoms**, where E_d is a displacement energy [1]. Reported This is an illustrative estimate, not a universal count of defects remaining after every ion impact.

Depending on species, dose and implantation temperature, damage can accumulate until part of the silicon becomes **amorphous**, losing its long-range crystalline order. Other implants leave damaged but still crystalline material [1]. Reported

Four requirements that must be met together

The post-implant anneal aims to remove damage, put dopants into electrically active configurations, restore carrier mobility and do all this with as little unwanted dopant movement as possible [1]. Reported **Activation and repair are related, but they are not the same measurement.** A wafer can have a largely recovered lattice while retaining inactive dopants or residual defects.

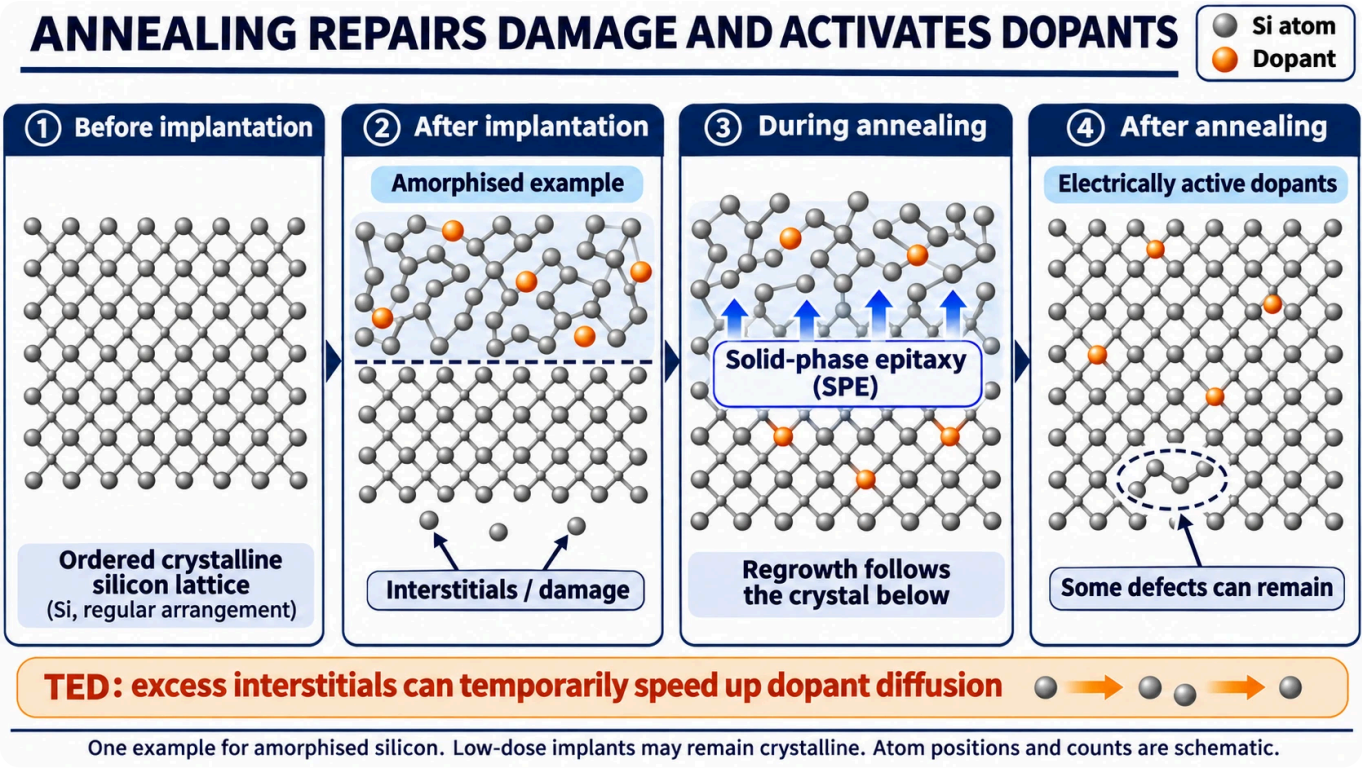


Figure 4 **From implantation damage to recovery and activation** (schematic)

Reading the figure

This sequence shows one case: an amorphised silicon layer regrowing from crystalline silicon underneath. Not every implant produces an amorphous layer. Orange spheres represent dopants schematically; their number and arrangement are not a measured concentration. Some defects and inactive dopants can remain after regrowth [1].

Solid-phase epitaxy: rebuilding from the crystal below

If the damaged surface layer is amorphous and a crystal remains beneath it, that crystal can act as a template. The interface advances through the disordered material without melting it. This is **solid-phase epitaxy (SPE)**. The handout shows electron micrographs of an antimony-implanted layer regrowing during annealing at **525 °C**, with observations at successive times [1]. Reported That temperature belongs to the example, not to every activation process.

In non-amorphised material, stable defects make activation more complicated. Boron can even exhibit **reverse annealing**, in which the electrically active fraction falls over part of an increasing-temperature sequence. Damage beyond the original amorphous/crystalline interface can also form secondary defects and contribute to enhanced diffusion [1]. Reported

Transient enhanced diffusion: damage leaves a moving legacy

After an implant, many displacement defects disappear quickly. A useful approximation, the **+1 model**, treats the remaining excess silicon interstitial population as roughly one interstitial per implanted ion [1]. Reported It is a model of the net excess, not a literal description of every collision cascade.

Interstitials can cluster into **{311} defects**. As these dissolve during annealing, they release interstitials and can temporarily accelerate dopant diffusion. This is **transient enhanced diffusion (TED)** [1]. Reported

One calculation in the handout shows a silicon interstitial concentration more than **10^5 times its equilibrium value** at 750 °C after 0.1 seconds [1]. Reported The multiplier describes interstitial supersaturation. It is not a claim that every dopant's diffusion coefficient increases by the same factor.

The handout identifies TED as a major influence on shallow junction depth in the processes it discusses. Because {311} defects can persist longer at a lower temperature, a lower-temperature anneal can sometimes produce more dopant redistribution for a comparable equilibrium diffusion budget [1]. Reported Lower temperature alone is therefore not a reliable guarantee of a sharper junction.

Connecting this lesson to thermal processing

Rapid thermal processing, flash lamps and lasers provide ways to deliver intense, short heating cycles. The goal is to obtain enough activation and repair while limiting diffusion. A Mattson technical presentation stresses that these objectives must be balanced: a millisecond pulse can be too short to complete some defect-repair processes [15]. Reported SCREEN describes millisecond flash-lamp heating as a route to high activation with a low thermal budget [16]. Reported Neither statement makes the shortest pulse universally best.

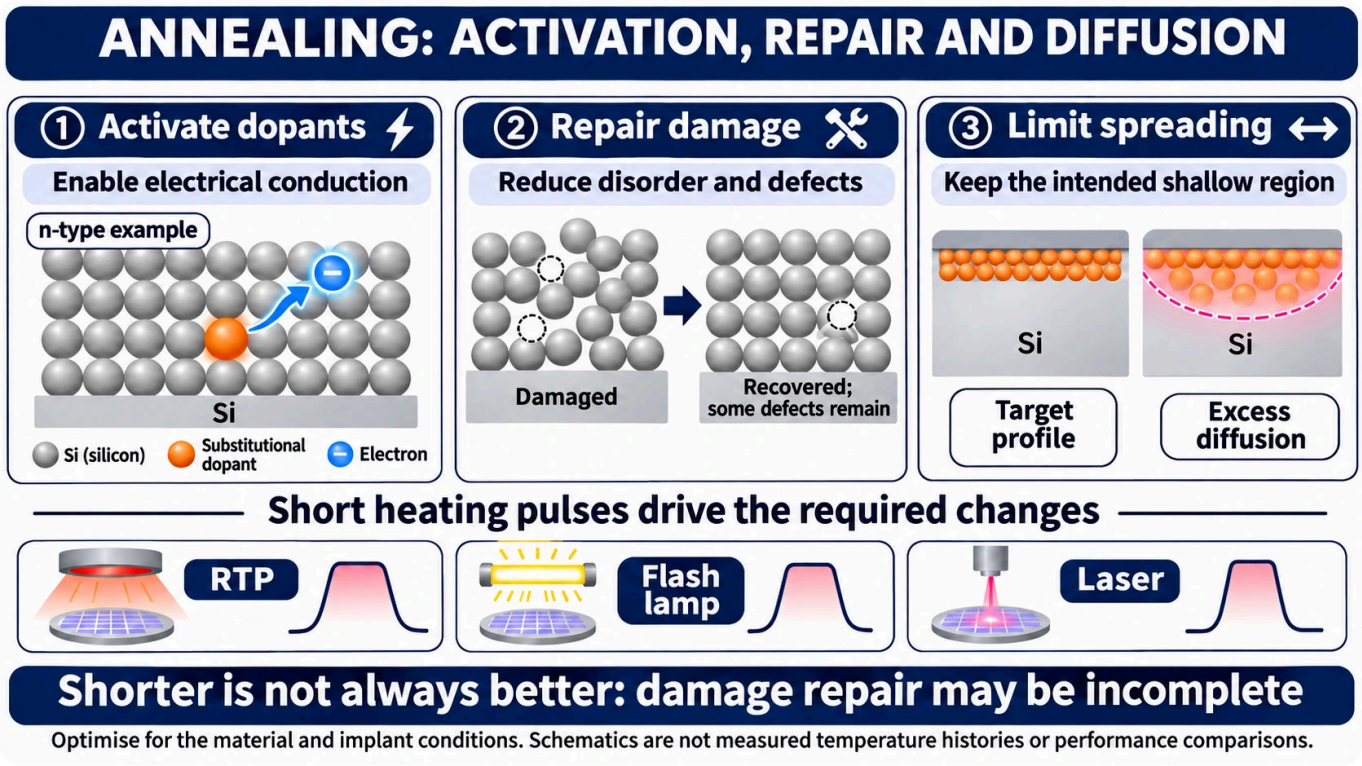


Figure 5 **Balancing activation, damage repair and diffusion** (schematic)

Reading the figure

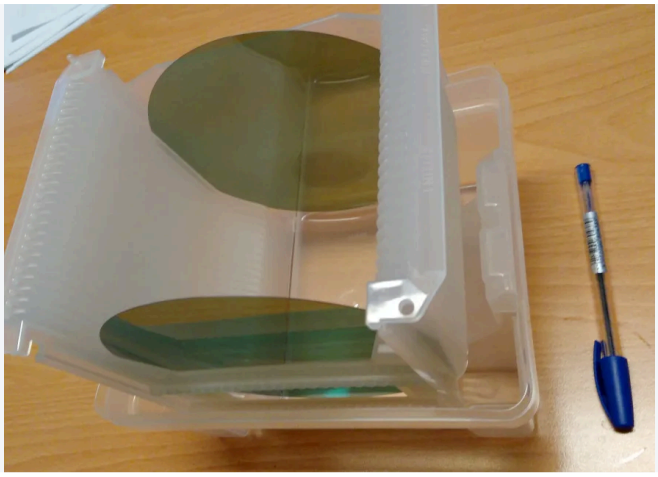
The donor-and-electron picture is an n-type example. Other dopants create holes instead. The thermal-processing icons illustrate methods; their pulse shapes are not measured histories or a comparison at equal conditions. The recipe must be chosen for the material, implant and required electrical profile [1][15][16].

6. Why SiC is implanted hot

Silicon carbide is used in power devices, including those that switch power in electric vehicles. Its implantation damage is difficult to remove by subsequent annealing. A Nissin technical report describes **heating the wafer during implantation** so that some damage can recover as it forms, reducing the accumulated damage [11]. Reported

The cited IMPHEAT system supports wafer temperatures from room temperature to **500 °C**, using a heated electrostatic chuck [11]. Reported This is a reported tool capability. Hot implantation controls damage during the implant; it does **not** remove the need for a later dopant-activation anneal.

Aluminium is commonly used to make p-type SiC regions. Nissin reports aluminium doses of the order of **10^{15} atoms/cm²** for SiC power-device manufacturing, and a newer source that reacts solid aluminium with chlorine gas to increase aluminium beam current by **40-60%** relative to its previous approach [12]. Reported The comparison is the supplier's reported result, not a benchmark across all available systems.



Two 6-inch (150 mm) SiC wafers in a carrier, as identified by Wikimedia Commons. SiC illustrates why implantation temperature is an important part of the recipe, alongside species, dose and energy [11].
Image: FDominec / Wikimedia Commons / CC BY-SA 4.0. Converted to WebP.

7. The global equipment landscape

- **Read the market figures with their boundaries intact**

A METI strategy document published in December 2025, using Global Net data, gives an ion implantation equipment market of **¥299.3 billion**. Its company shares are **Axcelis 51%** and **Applied Materials 28%** [9]. Reported Together, those shares total **79%**. Calculation The chart does not state the underlying market-data year or give a company-by-company breakdown of the remaining 21%. Its regional colouring indicates that much of the remainder is associated with Japanese suppliers, but it does not justify assigning every remaining percentage point to named companies [9]. Reported

The same document separately reports a **¥340.7 billion thermal-processing equipment market**, with Tokyo Electron at 42%, Applied Materials at 28% and NAURA at 8% [9]. Reported Thermal processing and ion implantation are different market categories; these shares should not be combined.

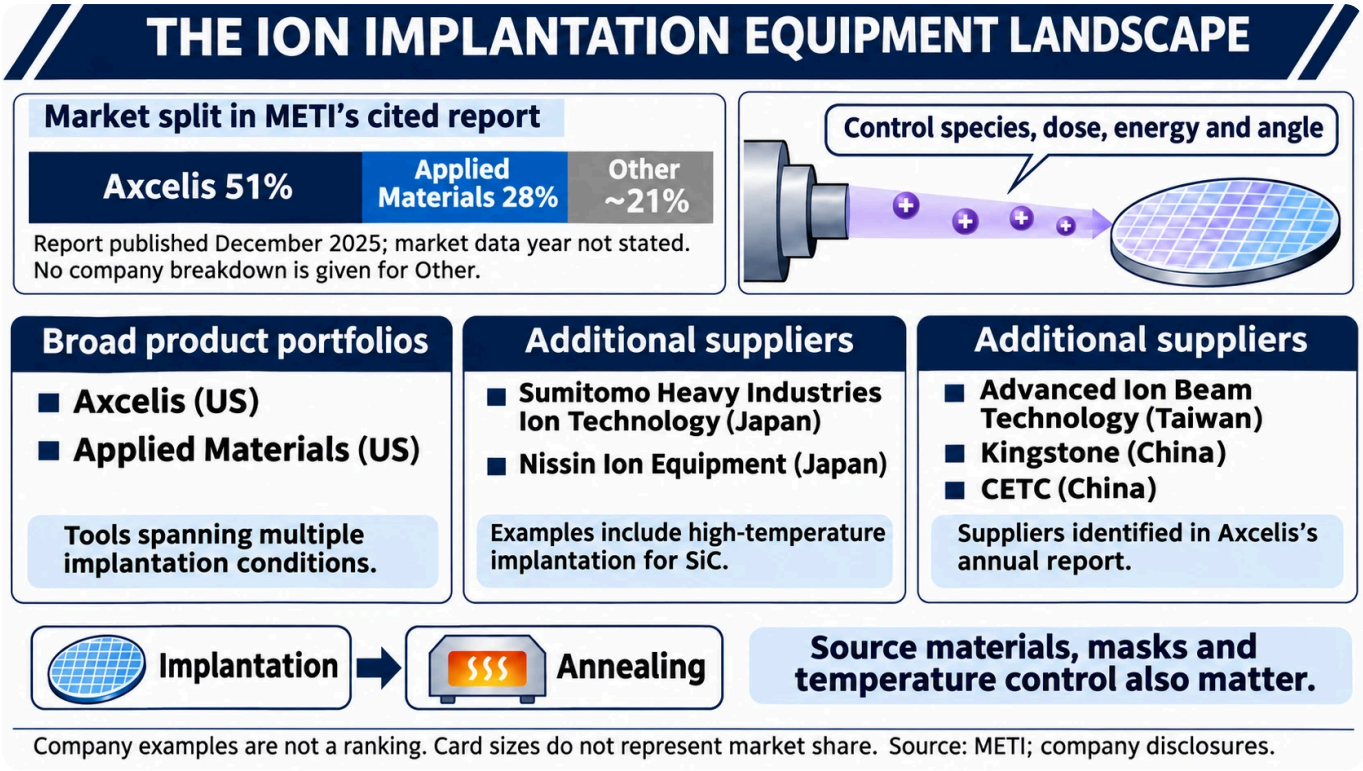


Figure 6 **Equipment suppliers and the cited market split** (schematic)

Reading the figure

The bar follows the cited METI market categories. December 2025 is the report's publication date, not a confirmed data year. The company cards provide examples from the article; their size and order do not represent market share, product quality or business relationships [7][9–12][14].

Two broad-portfolio suppliers

Axcelis Technologies, based in Massachusetts, is highly focused on implantation: its 2025 report attributes **98.2% of $839 million revenue** to that business. Its principal platform is Purion. The report identifies Applied Materials as its main implantation competitor and states that these two companies alone offer the full set of equipment categories it describes [7]. Reported That portfolio comparison is Axcelis's assessment.

Power-device applications accounted for **55% of Axcelis's 2025 systems shipment value**, according to the report. The company offers Purion Power products for applications including SiC and describes itself as a technology leader in this segment [7]. Reported The shipment percentage is a company mix figure, not its share of the power-device market.

Applied Materials includes ion implantation in its Semiconductor Systems business [14]. Reported The historical source records its introduction of the fully automated PI9000 implanter in 1985 [2]. Reported The fact that this article has more implantation-specific disclosure from Axcelis should not be read as a comparative judgement on tool performance.

Other suppliers and their backgrounds

Axcelis also identifies **Sumitomo Heavy Industries Ion Technology** and **Nissin Ion Equipment** in Japan, **Advanced Ion Beam Technology (AIBT)** in Taiwan, and **Kingstone Semiconductor** and **CETC** in China as competitors [7]. Reported Their coverage varies by application and equipment category.

The Sumitomo-related history is international. Peter Rose founded NOVA Associates in the US in 1978; the NV-10 high-current production tool followed in 1979, with beam current above 10 mA. The cited retrospective says its first machine was shipped to a Japanese customer that December. Sumitomo Heavy Industries brought accelerator experience to a joint venture with Eaton, which had acquired NOVA. The venture was established in 1983 and shipped its first domestically produced machine in 1984; a later name change occurred in 2006 [4]. Reported

Nissin Electric began a technical partnership with High Voltage Engineering Europe (HVEE) in 1973 and started implanter production in 1974. Nissin Ion Equipment was established in 1999, taking over manufacturing, and began delivering IMPHEAT in 2010 [10]. Reported Its cited technical report describes three business pillars: SiC power-device implantation, flat-panel-display implantation and support for installed equipment. It claims a 100% share in the specific category of implantation equipment for sixth-generation display glass substrates [12]. Reported This is a supplier claim about a defined display category, not the overall semiconductor implantation market.

Export controls: a dated business risk

Axcelis's 2025 annual report discusses US export restrictions and a new classification introduced in December 2024 for certain 300 mm implantation equipment. It says it could still serve nearly all its Chinese customers at the time of that report, while warning that tighter restrictions might encourage purchases from suppliers outside the US, including AIBT, Nissin and Sumitomo. It also describes Kingstone and CETC developing tools for the Chinese market [7]. Reported These statements describe the report's period and risk assessment, rather than a guide to current export permissions.

Axcelis and Veeco: a proposed combination

Axcelis agreed a merger with Veeco in September 2025. In their **2 November 2026** update, the companies said they expected completion by the end of the first quarter of 2027, subject to conditions. Chinese SAMR approval remained pending, and the parties planned a new US HSR submission because the existing clearance was approaching expiry. The timing was expressly not assured [8]. Reported

Veeco's disclosed technologies include laser annealing, ion-beam processes and MOCVD [8]. Reported One way to interpret the proposed combination is as bringing implantation and complementary thermal-processing capabilities into the same company. That is an interpretation, not evidence that a particular integrated process has already been commercialised. Interpretation

8. Materials and components behind the beam

An implanter depends on more than magnets and high voltage. Materials engineers contribute at several points.

- **Source materials.** Feed gases and solids must deliver the required dopant species reliably. The older Nissin SiC source used an aluminium-containing target with PF_3 assistance; its newer report describes solid aluminium reacting with chlorine [11][12]. Reported
- **Masks.** Photoresist defines the exposed region, but the required stopping thickness depends on the species and energy. A mask that is too thin cannot provide the intended protection [1][7]. Reported
- **Heated wafer supports.** Hot SiC implantation needs controlled heating and electrostatic clamping. Nissin describes design measures to accommodate thermal expansion and avoid wafer cracking or lifting [11]. Reported
- **Recovery of the material itself.** The implant and anneal must be developed together, especially where defects are difficult to remove, as in SiC [11]. Reported

Precision means controlling a distribution

A production implanter controls the total number, spatial distribution and energy of many incoming ions. It does not count out individual atoms and place each one at its final substitutional site. The crystal response and subsequent anneal are essential parts of the result.

9. What will determine progress?

Productivity in power devices is one pressure. Axcelis's reported shipment mix shows the importance of power applications [7], while Nissin describes cost demands from electric-vehicle manufacturers and the need for higher productivity [12]. Reported Higher beam current is useful only if dose uniformity, contamination, damage and wafer temperature remain acceptable.

Access to markets is another. Export restrictions can affect which tools customers can buy, and cross-border transactions require regulatory approvals [7][8]. Reported These are commercial constraints alongside the physics.

Joint optimisation of implantation and annealing connects the whole lesson. The electrical profile depends on where ions stop, what damage they create and how the subsequent heat treatment changes both [1][15]. Reported A good implant recipe cannot be judged independently of its activation process.

10. Review and the next lesson

Question	Key idea
Why implant?	Monitor dose electrically, use patterned masks and adjust dose and depth more independently than in thermal diffusion.
How is energy set?	E = qV; charge state matters as well as voltage.
How are species selected?	Magnetic trajectories depend on mass, energy and charge; a resolving slit selects the required beam.

Question	Key idea
How is dose measured?	Integrate current to obtain charge, then convert to ion count with the appropriate charge state and delivery corrections.
Where do ions stop?	A distribution described by projected range and straggle; channelling can create a deeper tail.
Why anneal?	Repair damage, activate dopants and restore transport properties while limiting redistribution.
What is TED?	Implant-induced excess interstitials can temporarily accelerate dopant diffusion during annealing.
Why implant SiC hot?	Reduce damage accumulation; a later activation anneal is still required.
Who supplies tools?	Axcelis and Applied Materials lead the cited market chart; additional suppliers operate in Japan, Taiwan and China.

Next is **Lesson 3-11: Chemical Mechanical Planarisation (CMP)**. After depositing films, etching patterns and implanting dopants, the wafer surface is no longer flat. CMP combines chemistry and mechanical action to restore the flatness needed for subsequent layers.

11. Check your understanding

1. Give two advantages of implantation over thermal diffusion.

▼ Show answer

Examples include electrical monitoring of dose, relatively low wafer temperature during the implant, patterned implantation through masks, and greater freedom to adjust dose and depth within tool and material limits. A later anneal is still needed.

2. Why can a magnetic analyser select one ion species?

▼ Show answer

In a transverse magnetic field, $r = \sqrt{(2mE)}/(qB)$. At the same energy and charge, different masses follow different radii. A resolving slit admits the desired trajectory.

3. Approximately how long does a dose of 10^{15} ions/cm² take on a 300 mm wafer at 1 mA?

▼ Show answer

About 110 seconds for singly charged ions, assuming constant current, uniform coverage and full beam delivery to the wafer. The area is about 707 cm² and the required charge about 0.11 C.

4. What is projected range? Is it always the depth of the concentration peak?

▼ **Show answer**

It is the mean penetration depth normal to the surface. It coincides with the peak in a Gaussian approximation, but not necessarily in an asymmetric real profile. ΔRp describes the standard deviation.

5. What is channelling, and how can it be reduced?

▼ **Show answer**

Ions aligned with open crystal directions avoid some close collisions and penetrate farther. A screen oxide, tilt and rotation can reduce it. The conventional 7° example is not a universal recipe.

6. What are the two main purposes of a post-implant anneal?

▼ **Show answer**

Repair implantation damage and make dopants electrically active. Restoring carrier mobility and avoiding excessive dopant redistribution are also important requirements.

7. Why can a lower-temperature anneal sometimes cause more redistribution than expected?

▼ **Show answer**

Defect clusters can persist longer and continue to release excess interstitials, producing transient enhanced diffusion. The complete temperature-time and defect history matters, not temperature alone.

8. Why implant SiC at an elevated wafer temperature?

▼ **Show answer**

Some damage can recover during implantation, reducing damage accumulation in a material whose defects are difficult to remove. This does not replace the later activation anneal. The cited IMPHEAT report gives a capability up to 500 °C.

9. Which two companies have the largest shares in the cited implantation market chart?

▼ **Show answer**

Axcelis at 51% and Applied Materials at 28%. The METI document was published in December 2025, but its chart does not state the market-data year.

12. Glossary

Ion implantation
Introducing ions into a wafer by accelerating them to a selected kinetic energy.

Thermal diffusion
Introducing or redistributing dopants using their thermally driven motion through a material.

Dopant
An intentionally added atom used to change electrical properties, such as boron, phosphorus or arsenic in silicon.

Dose
Number of incident ions per unit area, usually ions/cm²; conversion to dopant atoms requires care for molecular ions.

Ion source
The part of the system that produces and extracts ions from a feed material.

Mass analyser
A beam-selection system using magnetic deflection and an aperture; selection depends on charge and energy as well as mass.

Faraday cup
An electrode arrangement that collects a beam to measure its electrical current.

Medium-current, high-current and high-energy
Broad implanter categories addressing different dose and energy requirements.

Projected range (Rp)
Mean penetration depth measured normal to the wafer surface.

Range straggle (ΔRp)
Standard deviation of the projected depth distribution.

Nuclear and electronic stopping
Energy loss through interactions with atomic nuclei and with electrons, respectively.

Channelling
Deeper penetration along relatively open directions in an ordered crystal.

Screen oxide
A thin surface oxide used before implantation, including to reduce channelling.

Amorphous
Lacking long-range crystalline order.

Solid-phase epitaxy (SPE)
Regrowth of an amorphous layer from a crystalline template without melting.

Activation
Putting dopants into configurations that can contribute electrically active carriers.

Reverse annealing
A decrease in the active dopant fraction over part of an annealing-temperature range.

Interstitial
An atom occupying a position between the normal lattice sites.

{311} defects
Extended defects containing excess interstitials; their dissolution can release those interstitials.

Transient enhanced diffusion (TED)
Temporarily increased dopant diffusion associated with implantation-induced defects during annealing.

Silicon carbide (SiC)
A compound semiconductor of silicon and carbon used in power devices and other applications.

Hot implantation
Implantation performed with the wafer held at elevated temperature to control damage accumulation.

13. Primary sources and further reading

1. **J. D. Plummer, M. D. Deal and P. B. Griffin; Stanford EE212, 1999-2000, hosted by the University of Washington** — Class Handout #14: Ion Implantation, Chapter 8, pp. 1-25 — Read source
2. **Semiconductor History Museum of Japan** — Transition to implantation-based dopant introduction in the early 1980s (Japanese) — Read source
3. **Semiconductor History Museum of Japan** — Equipment and materials in the 1960s: ion implantation equipment (Japanese) — Read source
4. **Semiconductor History Museum of Japan; Semiconductor Senior Association Newsletter No. 53, October 2007** — Development history of the NV-10 high-current ion implanter and its production in Japan (Japanese) — Read source
5. **Semiconductor History Museum of Japan, Shimura archive** — Debate over ion implantation equipment (Japanese) — Read source
6. **W. Shockley, Bell Telephone Laboratories** — US Patent 2,787,564: Forming semiconductive devices by ionic bombardment; filed 28 October 1954, granted 2 April 1957 — Read source
7. **Axcelis Technologies** — Form 10-K for the year ended 31 December 2025, Items 1 and 1A — Read source
8. **Axcelis Technologies and Veeco Instruments** — Merger closing timing update, 2 November 2026; Form 8-K, Exhibit 99.1 — Read source
9. **Japan Ministry of Economy, Trade and Industry (METI)** — Future direction of the semiconductor and digital industry strategy, 23 December 2025, p. 5 (Japanese) — Read source
10. **Nissin Ion Equipment** — Company history (Japanese) — Read source
11. **Nissin Ion Equipment; Nissin Electric Technical Review, Vol. 58 No. 2, October 2013** — Development of the IMPHEAT ion implanter for SiC power devices (Japanese) — Read source
12. **Nissin Ion Equipment; Nissin Electric Technical Review, Vol. 69 No. 1, July 2024** — Technologies and achievements in 2023: ion implantation equipment (Japanese) — Read source
13. **PubChem, US National Institutes of Health** — Periodic Table of Elements: atomic weights and silicon density — Read source
14. **Applied Materials** — Form 10-K for the year ended 26 October 2025, p. 80 — Read source
15. **P. Timans and colleagues, Mattson Technology** — Flat-Top Flash Annealing; AVS JTG presentation, 18 July 2012 — Read source
16. **SCREEN Semiconductor Solutions** — LA-3100 flash-lamp annealing system — Read source

14. Claim-to-source guide

Topic	Evidence and limits
Implantation benefits, drawbacks and beamline	Stanford teaching material [1]; historical account [2]. General principles are distinguished from example process values.
Dose range, stopping mechanisms, projected range and Gaussian approximation	Stanford [1]. Real profiles need not be Gaussian.
Lateral spread, masks, channelling and conventional tilt	Stanford [1]. The 7° example is not a universal angle.
Damage, amorphisation, SPE, activation and reverse annealing	Stanford [1]. The 30 keV arsenic and 525 °C SPE cases are illustrative examples.
+1 model, {311} defects and TED	Stanford [1]. The 10^5 example concerns interstitial supersaturation, not a universal diffusivity multiplier.
Early adoption, production milestones and Japanese development programme	Historical sources [2–5]; each account has its own geographical and historical scope.
Shockley patent and inclusion of annealing	Patent [6], including filing and grant dates.
Typical implant count, equipment categories and beam ranges	Axcelis 2025 annual report [7].
Axcelis revenue mix, power-device shipment mix, competitors and business risks	Axcelis [7]. Corporate assessments are attributed, not treated as independent rankings.
Proposed Axcelis-Veeco merger and timing	Joint update dated 2 November 2026 [8]; closing remains conditional.
Implantation and thermal-processing market figures	METI report [9]. Publication date is known; chart data year and Other's company breakdown are not stated.
Nissin company history	Company history [10].
SiC hot implantation, chuck and multiply charged ion example	Nissin technical report [11]; the tool capability is not a universal SiC recipe.
Aluminium dose, source-current improvement and display-market claim	Nissin technical report [12]; comparisons and market claim are supplier-reported.
Atomic weights and silicon density	PubChem [13].
Applied Materials business scope	Company annual report [14].
Annealing trade-offs and short-pulse methods	Mattson technical presentation [15] and SCREEN product information [16].
Ion speeds, bend radii, isotope ratio, dose/time and atomic fraction	Calculations in this article using the stated assumptions and [13].
Interpretation of the proposed merger	Editorial interpretation, explicitly labelled as such.

Updated 8 November 2026. Technical explanations draw on the cited university teaching material, patents and industry publications. Company figures and historical statements are attributed to their sources. Market-report publication dates are distinguished from the underlying data year. Calculations use the assumptions stated beside them. Forward-looking statements are dated and are not confirmed outcomes.

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