



DEFECT ENGINEERING IN CRYSTALLINE SOLIDS

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Abstract

Crystalline solids are inherently imperfect. Each genuine crystal exhibits irregularities in the perfect periodic structure of atoms, and these irregularities — collectively referred to as defects — influence nearly all functional characteristics of technological significance, such as electrical conductivity, mechanical resilience, optical response, catalytic performance, and diffusion behavior. Defect engineering is the intentional incorporation, regulation, and alteration of these flaws to customize material characteristics for particular uses. This manuscript examines the categorization of crystallographic imperfections (point, line, planar, and volumetric defects), the thermodynamic and kinetic principles that dictate their emergence and stability, as well as the primary experimental and computational methodologies employed to manipulate defects, such as doping, ion implantation, irradiation, quenching, plastic deformation, and strain engineering. The discourse encompasses applications in semiconductor technology, structural ceramics, metallurgy, and energy materials, as well as the characterisation methods employed to measure fault populations. The article culminates in an examination of contemporary obstacles, notably the challenge of attaining atomic-scale regulation of defect type, concentration, and spatial arrangement, alongside nascent avenues like defect engineering in two-dimensional materials and machine-learning-assisted defect design.

1. Introduction

The traditional depiction of a crystal as an endless, flawlessly periodic arrangement of atoms serves as a beneficial abstraction, however no actual substance attains this level of perfection. Thermodynamics explicitly prohibits this: at any temperature exceeding absolute zero, the entropy increase from adding a finite concentration of point defects to an otherwise flawless lattice reduces the system's free energy compared to the defect-free condition. Defects are not simply random imperfections to be eradicated; rather, they are, in essence, a characteristic aspect of the equilibrium of crystalline substances. Throughout a significant portion of materials science history, flaws were predominantly perceived as contributors to deterioration – locations of mechanical fragility, electrical dispersion, or optical impairment. Dislocations were held responsible for the variance between the theoretical and actual strength of metals; vacancies were associated with diffusional creep; grain boundaries were regarded as impediments to conductivity. In recent decades, this viewpoint has undergone significant modification. Investigators have discovered methods to

deliberately incorporate and arrange imperfections to acquire characteristics that are unachievable in flawless crystals. The doping of silicon with boron or phosphorus, which is the cornerstone of semiconductor electronics, is merely the intentional insertion of substitutional point defects. The precipitation hardening of aluminum alloys depends on the designed configurations of coherent and incoherent precipitates. Color centers in diamonds, which serve as single-photon emitters and quantum detectors, are point defects formed during irradiation and subsequent annealing. This reorientation — from defect avoidance to defect engineering — today forms the foundation of entire subdisciplines in electronic materials, structural metallurgy, and quantum technology. It also signifies a wider transformation in the mindset of materials scientists regarding structure–property correlations:

instead of considering the ideal lattice as the benchmark and defects as mere disturbances to be reduced, defect engineering regards the defect population as a design parameter, on par with composition and processing methods, which can be defined, aimed at, and validated. This document examines the scientific principles and methodologies of defect engineering in crystalline materials. Section 2 categorizes the principal types of defects based on their dimensional characteristics. Section 3 examines the thermodynamic and kinetic principles behind defect generation, elucidating the inevitability of defects and the methods for predicting and regulating their equilibrium concentrations. Section 4 examines the primary engineering methodologies employed to create or alter flaws. Section 5 examines applications across several categories of materials. Section 6 succinctly addresses the characterization techniques required to authenticate defect engineering approaches, while Section 7 examines existing challenges and prospective avenues for development.

2. Classification of Crystallographic Defects

Crystallographic defects are conventionally classified according to their dimensionality.

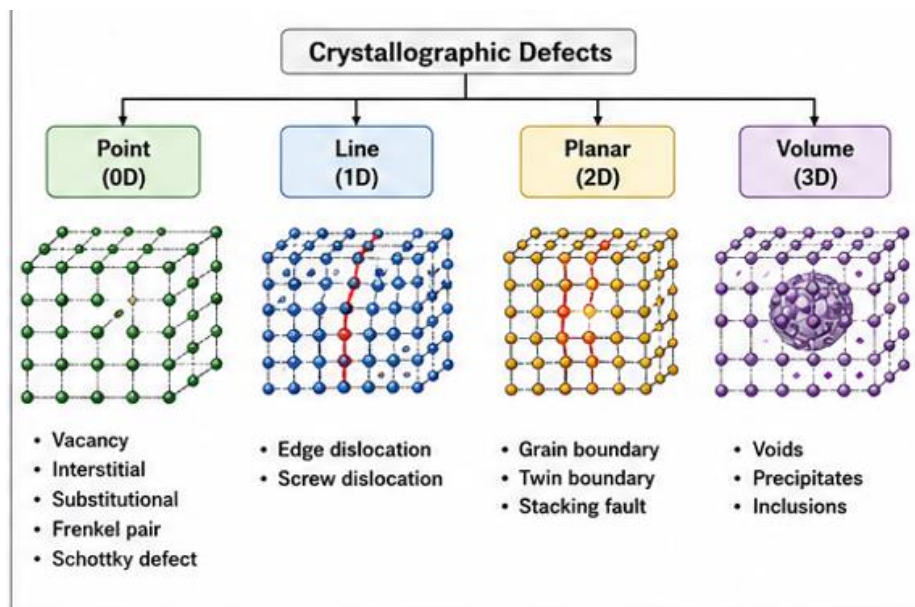


Figure 1. Classification of Crystallographic Defects

Table 1. Classification of Crystallographic Defects

Defect Type	Dimension	Examples	Effect on Properties
Point Defects	0D	Vacancy, Interstitial, Frenkel Pair	Diffusion, Electrical Conductivity
Line Defects	1D	Edge and Screw Dislocations	Plastic Deformation
Planar Defects	2D	Grain Boundaries, Twins	Strength, Corrosion Resistance
Volume Defects	3D	Voids, Inclusions, Precipitates	Mechanical Strength

2.1 Point Defects (Zero-Dimensional)

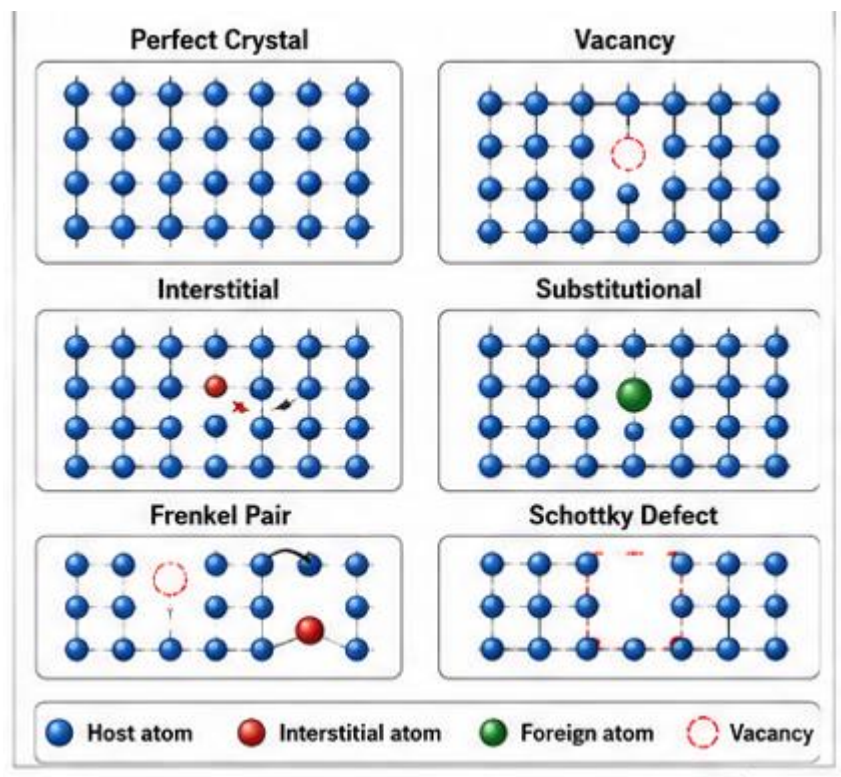


Figure 2. Types of Point Defects in Crystalline Solids

Point defects are localized disruptions of the lattice at a single atomic site. The principal types are:

- **Vacancies:** an atom missing from a lattice site that would otherwise be occupied in the perfect crystal.
- **Self-interstitials:** an extra atom of the host species inserted into a normally unoccupied interstitial position.
- **Substitutional impurities:** a foreign atom occupying a regular lattice site in place of a host atom.
- **Interstitial impurities:** a foreign atom occupying an interstitial site.
- **Frenkel pairs:** a vacancy paired with a nearby self-interstitial, generated when an atom is displaced from its lattice site into an interstitial position.
- **Schottky defects:** in ionic crystals, a stoichiometric set of cation and anion vacancies that preserves local charge neutrality.
- **Antisite defects:** in compound or ordered crystals, an atom of one sublattice occupying a site that should belong to the other sublattice.

Point flaws, despite their minimal size, have significant implications. In semiconductors, substitutional dopants regulate carrier density and classification; in ionic conductors, vacancies facilitate ionic movement; in metals, vacancies govern diffusion-dependent phenomena including creep and sintering.

2.2 Line Defects (One-Dimensional)

The dominant line defect is the **dislocation**, a linear discontinuity in the regular arrangement of atoms characterized by a Burgers vector that quantifies the magnitude and direction of lattice distortion. Two limiting types are recognized:

- **Edge dislocations**, in which an extra half-plane of atoms is inserted into the lattice, with the Burgers vector perpendicular to the dislocation line.
- **Screw dislocations**, in which the lattice is sheared such that atomic planes form a helical ramp around the dislocation line, with the Burgers vector parallel to the line.

Most dislocations observed in real crystals are of mixed character, combining edge and screw components. Dislocations are the primary carriers of plastic deformation in crystalline solids: their glide along preferred slip planes and directions accommodates shape change at stresses far below the theoretical shear strength of a perfect lattice. Dislocation density, typically expressed as total dislocation line length per unit volume, ranges from roughly 10^{10} to 10^{12} m^{-2} in well-annealed metals to $10^{15-16} \text{ m}^{-2}$ in heavily cold-worked material.

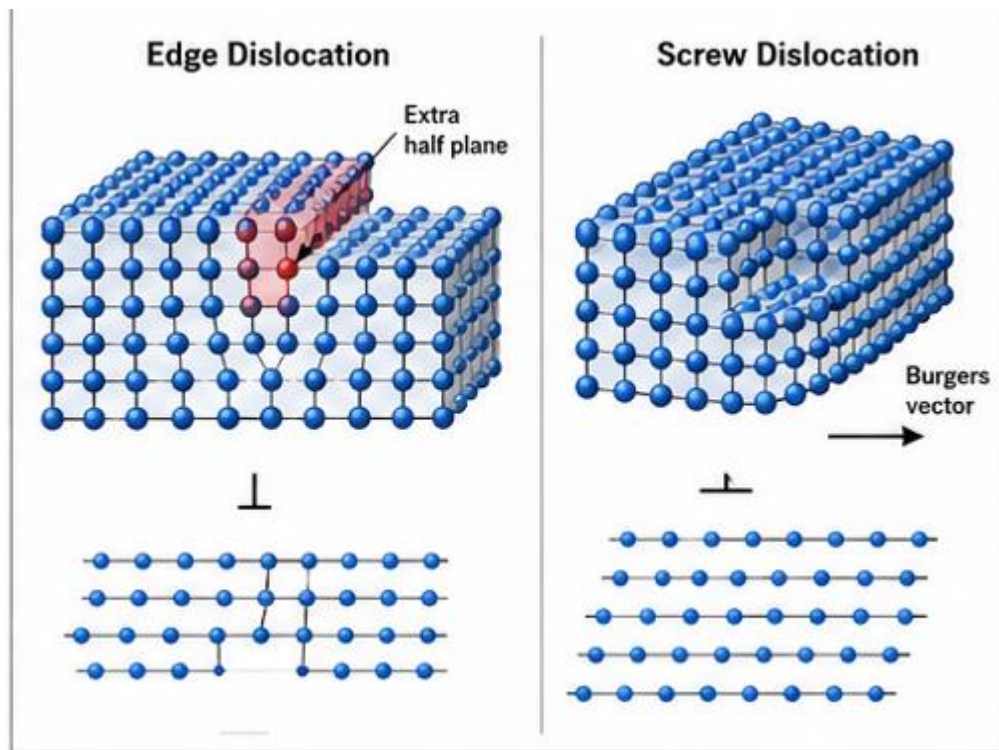


Figure 3. Edge and Screw Dislocations

2.3 Planar Defects (Two-Dimensional)

Planar defects are two-dimensional interruptions of lattice periodicity. Key examples include:

- **Grain boundaries**, interfaces separating crystallites of differing orientation in a polycrystalline solid. Low-angle grain boundaries can be described as arrays of dislocations; high-angle boundaries require more complex structural descriptions such as the coincidence site lattice model.
- **Stacking faults**, local interruptions in the normal stacking sequence of close-packed planes, bounded by partial dislocations.
- **Twin boundaries**, mirror-symmetric interfaces separating regions of a crystal that are crystallographically related by a twinning operation.
- **Antiphase boundaries**, found in ordered alloys, across which the sublattice occupancy pattern is shifted.
- **Free surfaces**, the ultimate planar defect, representing the termination of the crystal lattice and a region of markedly different bonding and energy compared with the bulk.

2.4 Volume Defects (Three-Dimensional)

Volume, or bulk, imperfections span three dimensions and encompass voids, precipitates, inclusions, and porosity. Precipitates of a secondary phase, regardless of being coherent, semi-coherent, or incoherent with the primary matrix, play a pivotal role in the strengthening mechanisms of several structural alloys. Voids and porosity, on the other hand, are typically detrimental, serving as locations for stress concentration, fracture initiation, and, in nuclear materials, radiation-induced expansion.

3. Thermodynamics and Kinetics of Defect Formation

3.1 Equilibrium Point Defect Concentration

The steady-state concentration of point defects results from a balance between the enthalpic expense of defect formation and the configurational entropy acquired by the random distribution of defects throughout the lattice sites. In a monatomic crystal, the minimization of Helmholtz free energy concerning vacancy concentration results in the well-known Arrhenius-type equation $n_v/N \approx \exp(-E_f/k_B T)$, where n_v denotes the number of vacancies, N represents the number of lattice sites, E_f signifies the vacancy formation energy, k_B is Boltzmann's constant, and T indicates the absolute temperature. Standard vacancy production energies in metals generally vary from approximately 0.5 to 1.5 eV, resulting in equilibrium vacancy percentages close to the melting point at 10^{-4} to 10^{-3} , which diminish exponentially as temperature decreases. This relationship is crucial to defect engineering since it demonstrates that the thermal history — the initial temperature of a material before quenching and the quenching rate — directly determines the defect population retained at ambient temperature.

The formation of a Frenkel pair necessitates the concurrent generation of a vacancy and an interstitial, with the equilibrium concentration exhibiting an analogous exponential relationship dictated by the pair formation energy, which is generally greater than that of a solitary vacancy due to the high energy cost of interstitial formation in densely packed structures.

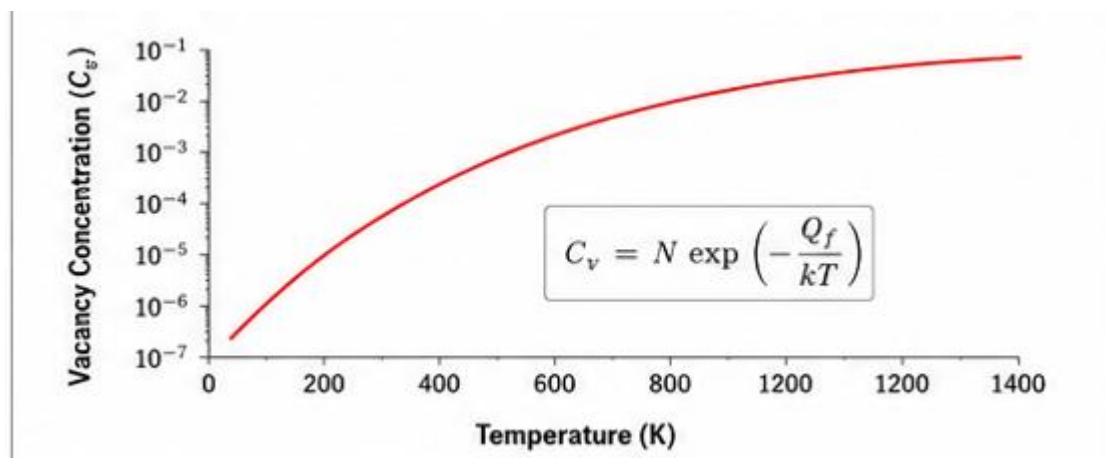


Figure 4. Effect of Temperature on Vacancy Concentration

3.2 Non-Equilibrium Defect Populations

Numerous defect populations of technical significance are not characteristics of equilibrium but are instead kinetically trapped or influenced by external forces. Swift cooling from elevated temperatures can entrap a supersaturation of vacancies significantly above the equilibrium concentration at lower temperatures, as the diffusion required for vacancies to relocate to sinks (surfaces, grain boundaries, dislocations) and be eliminated becomes insufficiently rapid to match the cooling rate. This supersaturation subsequently induces phenomena such as vacancy aggregation, void creation, and dislocation loop emergence. In a similar manner, exposure to high-energy particles (neutrons, ions, or electrons) consistently creates Frenkel pairs at a rate significantly surpassing thermal generation, resulting in stable defect concentrations that rely on the equilibrium between the production rate and the recombination or sink-mediated annihilation rate.

3.3 Defect Interactions and Complexes

Point faults seldom exist in isolation at significant concentrations; they engage with one another and with extended flaws. Vacancies may associate with substitutional impurities to create vacancy-impurity pairs, which play a crucial role in dopant diffusion processes in semiconductors. Interstitials produced during irradiation may cluster into dislocation loops or, when combined with vacancies, induce void swelling in reactor materials. The partitioning of impurities to grain boundaries and dislocation cores (Cottrell atmospheres) alters local mechanical and electronic properties and constitutes a method of defect engineering when executed intentionally, such as in grain-boundary segregation engineering for enhanced corrosion resistance.

3.4 Defect-Mediated Diffusion

Numerous significant kinetic phenomena in crystalline solids — such as solid-state diffusion, sintering, creep, and precipitation — occur through defect-mediated atomic transport instead of direct atom-to-atom exchange, which is energetically unfeasible in densely packed structures. The vacancy process, when an atom transitions to a nearby unoccupied site, is the primary diffusion route in the majority of metals and numerous ionic solids. The diffusion coefficient can be expressed as the multiplication of the equilibrium vacancy concentration and the vacancy jump frequency, indicating that manipulating the vacancy population directly influences the material's diffusivity. Interstitial diffusion, characterized by the movement of diminutive solute atoms like carbon or hydrogen through interstitial positions without necessitating a vacancy, generally occurs at a significantly accelerated rate and is utilized in procedures like the case-hardening of steel via carburization. Grain boundaries and dislocation cores function as efficient diffusion pathways with activation energies significantly lower than those of bulk lattice diffusion, allowing for the manipulation of the density and nature of these extended defects to enhance or, in certain barrier-layer scenarios, inhibit mass transport.

4. Techniques for Defect Engineering

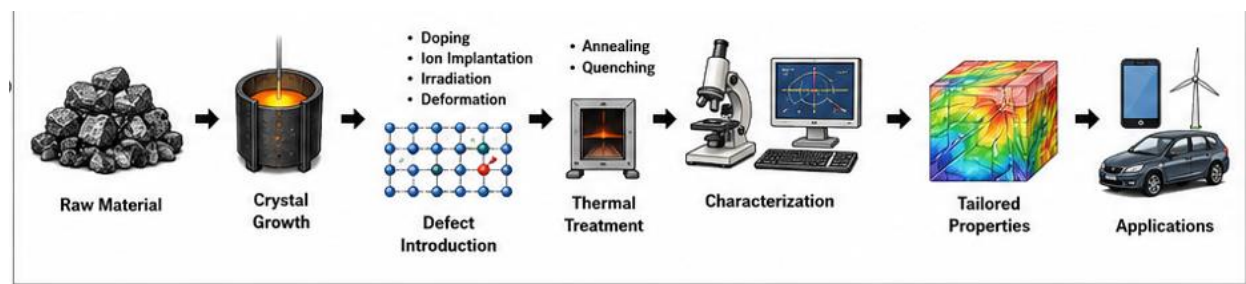


Figure 5. workflow of Defect engineering

Table 2. Defect Engineering Techniques

Technique	Defect Produced	Advantages	Typical Applications
Doping	Substitutional Defects	Controls Conductivity	Semiconductors
Ion Implantation	Vacancies, Interstitials	Precise Control	Microelectronics
Annealing	Vacancy Reduction	Stress Relief	Metals
Plastic Deformation	Dislocations	Strengthening	Structural Alloys
Strain Engineering	Misfit Dislocations	Higher Carrier Mobility	Transistors
Additive Manufacturing	Grain Refinement	Improved Strength	Aerospace

4.1 Doping and Alloying

The incorporation of substitutional or interstitial impurities during crystal formation or later processing is the most prevalent method of defect engineering. In semiconductor technology, regulated doping with donor or acceptor elements determines carrier type and density, establishing the foundation for p-n junctions, transistors, and nearly all solid-state electronic devices. Doping concentrations are meticulously calibrated throughout a wide range, from parts-per-billion for high-purity detector-grade substances to percent-level doping in heavily doped contacts.

4.2 Ion Implantation and Irradiation

Ion implantation facilitates the accurate and spatially confined insertion of dopant or defect entities by propelling ions to regulated energies and guiding them towards a target. The depth profile of implantation is determined by the stopping power of the target substance and can be adjusted via the ion energy and type, allowing for precise regulation of defect and dopant depth distribution. The process of implantation unavoidably causes lattice damage characterized by vacancies and interstitials, alongside the implanted species; subsequent annealing is generally necessary to recover crystallinity while preserving the intended dopant arrangement. In addition to the introduction of dopants, the intentional irradiation with electrons, neutrons, or heavy ions is employed to generate particular point-defect populations, such as nitrogen-vacancy centers in diamond, formed through nitrogen doping, followed by electron or ion irradiation and subsequent annealing to facilitate the movement of vacancies to substitutional nitrogen atoms.

4.3 Thermal Processing: Quenching and Annealing

Heat treatment protocols serve as a fundamental mechanism for regulating defect populations. Swift cooling from high temperatures captures a supersaturation of vacancies and can inhibit equilibrium phase transformations, preserving metastable configurations like supersaturated solid solutions that are later aged to yield fine, strengthening second-phase particles. In contrast, controlled annealing facilitates the migration, recombination, or coarsening of defects, serving to alleviate undesirable damage (such as post-implantation annealing in semiconductor fabrication) and to tailor specific microstructures (like recrystallization annealing for grain size regulation or precipitation annealing for the enhancement of age-hardened alloys).

4.4 Plastic Deformation and Severe Plastic Deformation

Mechanical deformation generates and proliferates dislocations, and at elevated strains can reduce grain size to the nanocrystalline scale via methods like equal-channel angular pressing, high-pressure torsion, and accumulative roll bonding. These intense plastic deformation methods are intentionally employed to develop elevated dislocation densities and ultrafine grain configurations that provide significant reinforcement via the Hall–Petch correlation and forest-dislocation hardening.

4.5 Strain Engineering

The epitaxial deposition of thin films on substrates with varying lattice parameters induces regulated elastic strain, and, after reaching a certain thickness, plastic strain through misfit dislocations. This strain alters the band structure, carrier mobility, and defect formation energies, and is intentionally utilized in strained-silicon transistor channels to improve carrier mobility, as well as in strain-engineered heterostructures for optoelectronic applications.

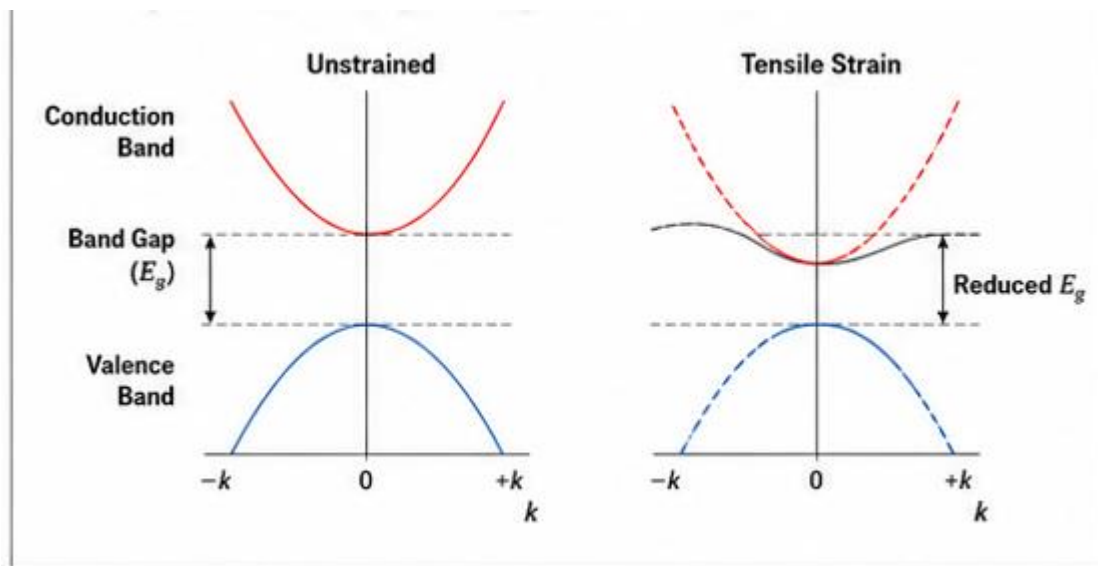


Figure 6. Strain Engineering in Crystalline Solids

4.6 Chemical and Electrochemical Methods

The populations of point defects, especially vacancies in oxides, can be regulated by the surrounding chemical milieu. The partial pressure of oxygen during the synthesis or subsequent annealing of metal oxides directly influences the concentration of oxygen vacancies, which subsequently regulates electronic conductivity, catalytic performance, and ionic transport in materials like cerium oxide and titanium oxide. Electrochemical biasing can also be employed to introduce or remove oxygen vacancies in situ, a technique utilized in resistive switching memory devices.

4.7 Additive Manufacturing and Rapid Solidification

Additive manufacturing techniques like laser powder-bed fusion and directed energy deposition include exceedingly rapid, spatially confined melting and solidification, with cooling rates frequently surpassing 10^3 – 10^6 K per second. The swift solidification inhibits equilibrium segregation and can broaden solid solubility significantly beyond equilibrium thresholds, resulting in supersaturated solid solutions, enhanced grain structures, and distinctive sub-grain cellular dislocation networks due to the steep thermal gradients and solidification rates present. Due to the ability to manipulate the thermal history at each location in a printed component via scan strategy, laser intensity, and scanning velocity, additive manufacturing is progressively regarded as a medium for spatially resolved defect engineering, allowing for intentional variation of grain size, texture, and defect density within a single part to satisfy localized property demands. Porosity, an undesirable volumetric flaw prevalent in additively made components due to gas entrapment or inadequate melt-pool fusion, continues to be a significant processing obstacle and a focus of ongoing process-parameter refinement.

5. Applications of Defect Engineering

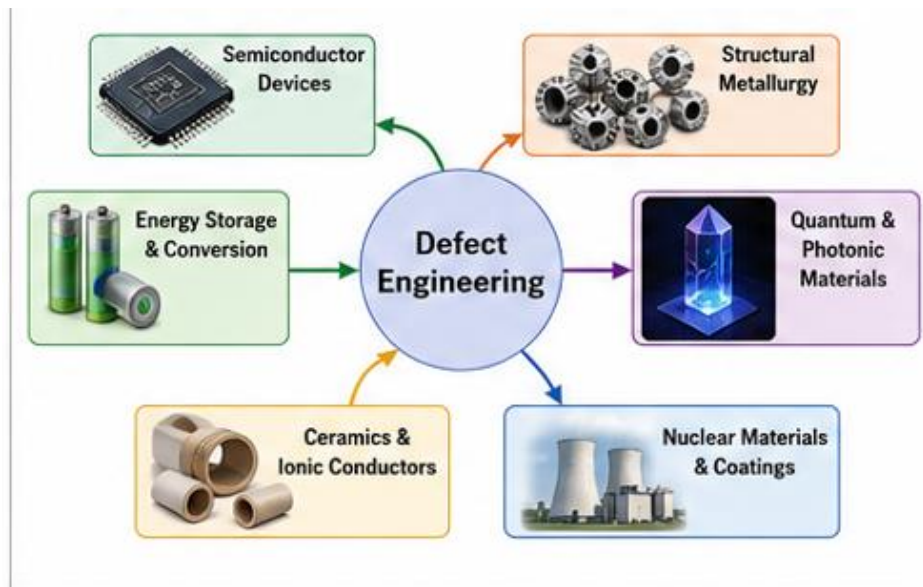


Figure 7. Major application area of Defect engineering

Table 4. Applications of Defect Engineering

Material	Engineered Defect	Property Improved	Application
Silicon	Dopants	Conductivity	Integrated Circuits
Diamond	NV Centers	Quantum Sensing	Quantum Computing
Zirconia	Oxygen Vacancies	Ionic Conductivity	Fuel Cells
Aluminum Alloy	Precipitates	Strength	Aerospace
Steel	Dislocations	Hardness	Automotive

5.1 Semiconductor Devices

Defect engineering is fundamentally integral to contemporary microelectronics. Regulated doping determines the electrical properties of devices; designed defect gettering sites are employed to capture undesirable metallic contaminants from active device areas; and the deliberate incorporation of deep-level defects is utilized to adjust carrier lifetimes in power devices, where rapid switching necessitates brief minority-carrier lifetimes attainable via platinum or gold doping, or through electron irradiation.

5.2 Structural Metallurgy

Precipitation hardening, solid-solution strengthening, and grain-boundary strengthening are defect-engineering techniques utilized to enhance the mechanical properties of structural alloys. In precipitation-hardened aluminum and nickel-based superalloys, the dimensions, coherence, and distribution of secondary-phase precipitates are meticulously designed via compositional adjustments and thermal treatment protocols to enhance resistance to dislocation movement while preserving ductility.

5.3 Ceramics and Ionic Conductors

The manipulation of oxygen vacancies in fluorite- and perovskite-structured oxides is fundamental to solid oxide fuel cell electrolytes, oxygen sensors, and catalytic supports. Introducing lower-valence cations into yttria-stabilized zirconia creates a compensatory array of oxygen vacancies, significantly improving ionic conductivity compared to the undoped variant.

5.4 Quantum and Photonic Materials

Point defects exhibiting clearly defined, accessible electronic and spin states — known as color centers — have emerged as essential in the realm of quantum information research. The nitrogen-vacancy center in diamond and similar defects in silicon carbide are produced using a blend of doping, irradiation, and annealing to function as single-photon emitters, qubits, and nanoscale magnetic field sensors that operate at ambient temperature.

5.5 Nuclear Materials

Radiation-induced defects — Frenkel pairs, dislocation loops, voids, and their agglomerates — govern the performance and lifetime of materials in nuclear reactor environments. Defect engineering in this context is largely about mitigation: designing alloys and microstructures (for example, oxide-dispersion-strengthened steels with a high density of nanoscale particle interfaces) that provide abundant defect sinks to suppress void swelling and radiation embrittlement.

5.5.1 Coatings and Surface Engineering

Surface and near-surface defect populations, which differ from bulk defects, are intentionally designed in coatings that resist wear and corrosion. Shot peening and laser peening generate a substantial concentration of near-surface dislocations and compressive residual stress, which delays the onset of fatigue cracks in aerospace and automotive parts. Physical and chemical vapor deposition techniques facilitate the

autonomous regulation of coating grain dimensions, columnar defect architecture, and residual stress conditions via deposition temperature, pressure, and ion bombardment energy, thereby permitting the simultaneous engineering of coatings for hardness, adhesion, and thermal-barrier efficacy.

5.6 Energy Storage and Conversion Materials

Defect chemistry is pivotal in the investigation of batteries and catalysis. Cation vacancies, antisite flaws, and oxygen non-stoichiometry in lithium- and sodium-ion battery electrode materials affect ion diffusion routes, voltage characteristics, and cycling durability. Intentional cation-disorder manipulation has been employed to establish percolating diffusion pathways in otherwise inadequately conductive rock-salt-structured cathode materials, significantly enhancing rate performance. In heterogeneous catalysis, designed surface oxygen vacancies and step-edge imperfections on oxide and metal catalysts generate under-coordinated active sites with altered adsorption energies, often improving catalytic performance and selectivity compared to flawless surfaces. Photocatalytic and photovoltaic substances exhibit comparable sensitivity to point-defect concentrations, as deep-level defects may serve as non-radiative recombination sites that diminish device performance, prompting defect-passivation approaches like halide or hydrogen treatment for perovskite and silicon photovoltaic absorbers, respectively.

6. Characterization of Engineered Defects

The validation and quantification of defect populations are integral to defect engineering methodologies. Concentrations of point defects and their electronic properties are typically investigated using positron annihilation spectroscopy, electron paramagnetic resonance, deep-level transient spectroscopy, and photoluminescence. Dislocation densities and configurations are analyzed by transmission electron microscopy, X-ray diffraction line-profile assessment, and electron channeling contrast imaging. The structure and chemistry of grain boundaries are examined using high-resolution and scanning transmission electron microscopy alongside energy-dispersive spectroscopy, and more frequently through atom probe tomography, which provides three-dimensional, near-atomic-resolution chemical mapping at interfaces. Atomistic and first-principles computational techniques, such as density functional theory assessments of defect production and migration energies, enhance experimental efforts by forecasting defect stability and informing processing design prior to synthesis.

A significant contemporary trend involves the integration of these methodologies into correlative, multi-modal workflows, where the identical area of a specimen is analyzed in succession by multiple probes — such as atom probe tomography for three-dimensional chemical analysis followed by transmission electron microscopy for structural context — enabling the correlation of composition, structure, and defect characteristics at the same physical site rather than deducing them from distinct specimens. In situ characterization, where a specimen is subjected to heating, strain, irradiation, or electrical bias during direct observation, has gained significance as it enables the dynamic observation of defect nucleation, migration, and interaction instead of relying on before-and-after images. In situ capabilities are especially advantageous for defect engineering as they enable the direct validation of processing-structure connections, rather than relying on ex situ data obtained after a specimen has transitioned to a different defect state.

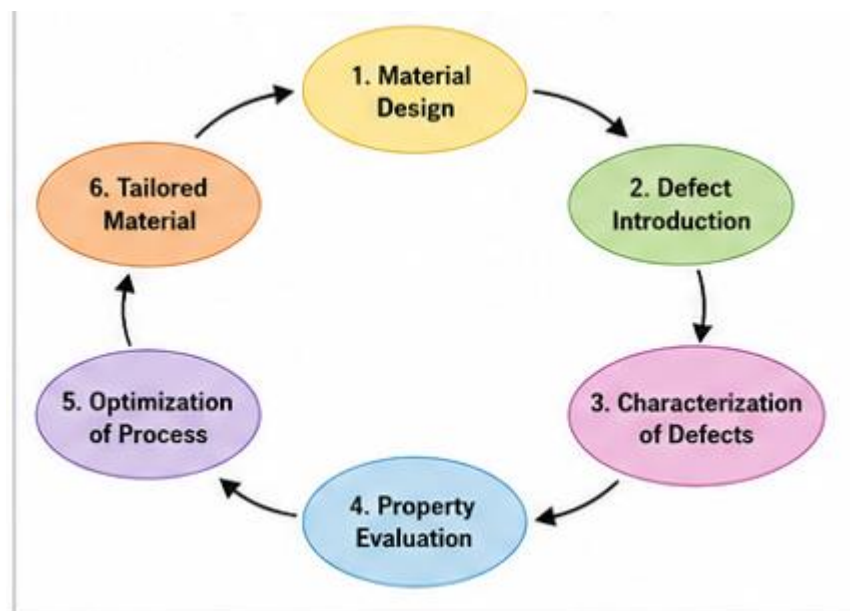


Figure 8. Defect engineering cycle

Table 3. Characterization Techniques

Technique	Information Obtained	Resolution
SEM	Surface Morphology	High
TEM	Dislocations & Atomic Structure	Atomic
XRD	Crystal Structure	Bulk
EPR	Electronic Defects	Atomic
PAS	Vacancy Defects	Atomic
APT	3D Atomic Composition	Atomic

7. Challenges and Future Directions

Notwithstanding significant advancements, various obstacles hinder the accuracy of defect engineering. Initially, attaining a deterministic, atom-by-atom arrangement of singular defects — rather than statistical regulation of an ensemble concentration — continues to pose challenges beyond specialized methods like scanning-probe atom manipulation or focused ion beam writing at minimal fluence, both of which are time-consuming and not easily scalable. Secondly, numerous defect engineering methodologies yield not merely one type of defect but rather a spectrum of varieties, hence complicating the analysis of structure–property correlations. Third, defects engage with one another in manners that are challenging to foresee based only on single-defect thermodynamics, especially at elevated concentrations pertinent to extensively doped or strongly irradiated substances. Fourth, methods for characterizing specific point defects in three-dimensional bulk materials, as opposed to surfaces or thin samples, are still constrained.

Anticipating the future, numerous avenues seem auspicious. Defect engineering in two-dimensional materials, where each atom functions as a surface atom and imperfections can significantly influence electrical and catalytic properties, is a rapidly expanding field. Machine-learning interatomic potentials are starting to enable extensive, high-accuracy simulations of defect creation, movement, and interaction at time and length scales that were previously unattainable with first-principles techniques, thus facilitating computationally informed defect engineering. Ultimately, the integration of defect engineering with quantum technology — employing individually addressable point defects as qubits or single-photon

emitters — is expected to sustain the demand for increasingly precise and deterministic defect fabrication methods.

8. Conclusion

Defects are an inherent and thermodynamically unavoidable characteristic of crystalline solids, and the intentional manipulation of their type, density, and spatial configuration — known as defect engineering — has emerged as a fundamental principle in contemporary materials science. Engineered defects, ranging from point defects that determine semiconductor conductivity to dislocations that influence mechanical strength, and from grain boundaries that regulate ionic transport to color centers that facilitate quantum sensing, are fundamental to a remarkable array of technologies. Ongoing improvements in synthesis accuracy, in situ and multi-dimensional analysis, and computational defect modeling will enhance the scope of defect engineering, especially in nascent fields like low-dimensional materials and quantum device technology. The discipline is transitioning from an empirical, trial-and-error methodology—where processing routes are modified and properties are subsequently assessed—to a predictive, design-oriented framework that first defines the desired defect population, derives the necessary processing route from thermodynamic and kinetic models, and then confirms it through targeted characterization. Achieving this vision completely will necessitate a more cohesive integration of synthesis, in situ characterisation, and computational defect modeling than what is typically practiced in most laboratories; nonetheless, the evolution of the discipline over the last twenty years indicates that such integration is feasible.

References

1. Kittel, C. *Introduction to Solid State Physics*. Wiley.
2. Hull, D., Bacon, D. J. *Introduction to Dislocations*. Butterworth-Heinemann.
3. Was, G. S. *Fundamentals of Radiation Materials Science*. Springer.
4. Tilley, R. J. D. *Defects in Solids*. Wiley.
5. Porter, D. A., Easterling, K. E., Sherif, M. Y. *Phase Transformations in Metals and Alloys*. CRC Press.
6. Sze, S. M., Ng, K. K. *Physics of Semiconductor Devices*. Wiley.
7. Doherty, R. D. et al. Current issues in recrystallization: a review. *Materials Science and Engineering A*.
8. Doherty, M. W. et al. The nitrogen-vacancy colour centre in diamond. *Physics Reports*.
9. Callister, W. D., Rethwisch, D. G. *Materials Science and Engineering: An Introduction*. Wiley.
10. Ashby, M. F., Jones, D. R. H. *Engineering Materials 1 and 2*. Butterworth-Heinemann.