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Joint ICTP-IAEA Workshop on Physics of Radiation Effect and its Simulation for Non-Metallic Condensed Matter

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Overview of non-metallic materials for fusion applications

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Joint ICTP-IAEA Workshop on Physics of Radiation Effect and its Simulation for Non-Metallic Condensed Matter

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IAEA

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OUTLINE

Overview of non-metallic materials for fusion applications.......................................I (Monday)

- An experimental fusion reactor. An example: ITER
- Introduction
  - Insulator materials for Fusion reactors
- Radiation damage
  - Effects of radiation damage
  - Effects of radiation damage on insulators
  - Candidate materials
- Insulators degradation under radiation. An example: Behaviour of insulating materials surface under irradiation
- Conclusions

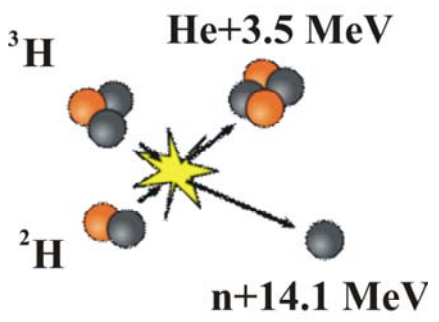
OUTLINE

Overview of non-metallic materials for fusion applications................................II (Wednesday)

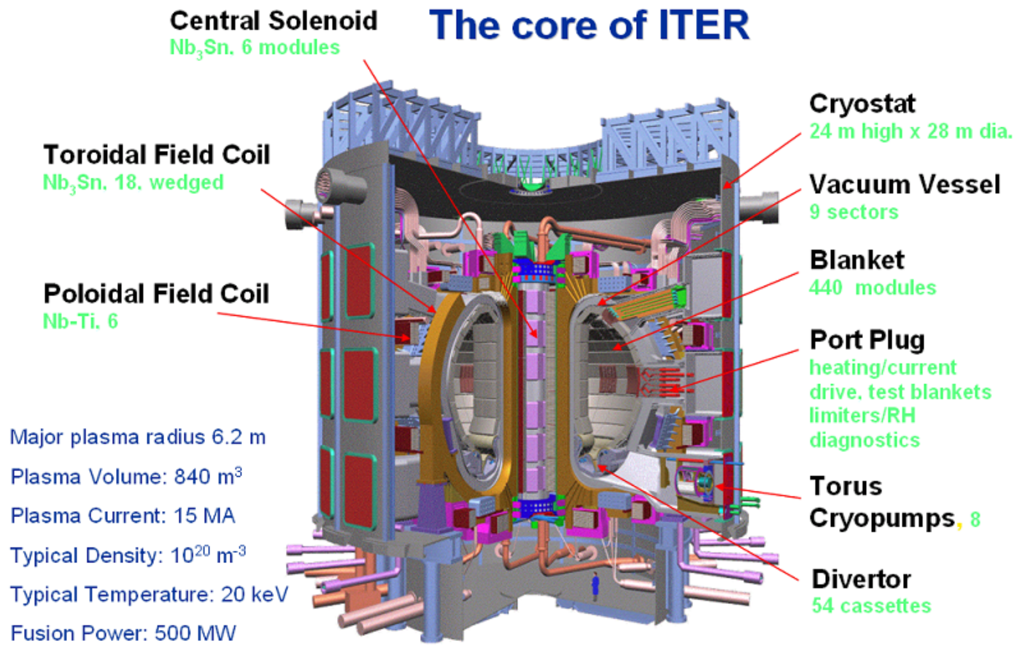
- Optical materials.
- Dielectric Materials.
- Breeder Materials: Li-ceramics and eutectic LiPb.
- Coating materials for Blankets.

Introduction *(i)*

1. An experimental fusion reactor: an example - ITER



Fusion reaction in ITER



The ITER (International Thermonuclear Experimental Reactor) device is based on the tokamak concept, in which a hot gas is confined in a torus-shaped vessel using a magnetic field.

The aim of ITER is to show that fusion could be used to generate electrical power, and to obtain the necessary data to design and operate the first electricity-producing plant.

Introduction *(i)*

- The ignited plasma will give rise to **high energy neutron** and **gamma radiation fluxes**, extending well beyond the first wall, together with an intense **particle flux on the plasma facing materials**.

- Insulators in **Fusion reactors** will be subjected to bombardment of particles, mainly due to acceleration of the residual gas due to local electric fields. **BULK + SURFACE damage**

- The radiation field will induce numerous different types of **defects** in the materials through **displacement and ionization processes**. In addition **transmutation products** from the nuclear reactions will build up with time representing impurity changes in the materials, as well as a source of possible activation.

Introduction *(ii)*

- Defect creation causes **changes in the materials**, and therefore in their properties.
- The nature of non- metallic materials makes them **highly sensitive to both ionization and displacement damage,** with the result that the properties of interest may be severely modified even at low dose rates and for low doses.
- All these processes have very important consequences from the point of view of the machine operation, lifetime and reliability.

Introduction *(iii)*

- **Radiation induced modification of the material properties is a technological problem** (but is also an attractive phenomenon from the point of view of the basic physics and the understanding of the basic processes which occur in the materials subjected to a field of radiation)

- Insulators are required in **critical components of a number of different systems**, such as high power RF windows (ICRH, ECRH), neutral beam injection (NBI) system, etc.. Hence changes in their properties may have serious consequences for the viability of the machine.

- Also ceramic breeders materials suffer **severe degradation** of their properties due to radiation.

Introduction *(iv)*

Insulator materials for Fusion reactors

- **Presence of a significant radiation field**, extending well beyond the first wall.

- The nature of insulating materials makes them **highly sensitive to both ionization and displacement damage**. Important properties of insulators degrade for only a few Gy/s and doses well below 1 dpa.

- **Insulators are key issues since they affect not only the operation and control, but also the safety of the machine.**

- Insulator materials are **critical components of a number of different systems**: RF window, NBI, cables, wires, etc. employed in many diagnostic and remote handling systems.

Radiation Damage *(i)*

General effects of radiation

- Ionization
  ↳ **ELECTRONIC EXCITATION**
  (exciton)
- Atomic displacements
- Impurity production
- Energy release into the material

Types of radiation

- Charged particles
  ↳ Ions
  - **Electronic excitation**
  - **Nuclear collisions**

  ↳ β
  - **Ionization**
  - Bremsstrahlung
  - Nuclear collisions
- Neutral radiation
  ↳ Photons
  ↳ Neutrons

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Defects produced by radiation

- Electronic defects
- **Ionic defects** → **VACANCIES / INTERSTITIALS**
- Extended defects

Frenkel pair: a vacancy-interstitial pair is formed when an atom is displaced from a lattice site to an interstitial site.

Effects of radiation damage

Displacement damage produces in all materials;

Vacancy + interstitial defects (point defects)
Aggregation of defects

Ionization produces in insulators;

changes in electronic charge distribution

(mainly heating in metals)

Materials are modified

Result ===>

changes in the physical and mechanical properties

Unfortunately, in general, the result is degradation

For example;

Materials swell	**--> distortions**
Become brittle	**--> break**
Corrode easier	**--> leaks**
Resistance decrease	**--> Joule heating, breakdown**
Optical absorption	**--> light transmission loss**

Effects of radiation on insulators

- **Ionizing** ⇨ **e-h pairs are created**

⇩

(NON PERMANENT Effect) **ΔConductivity, ΔTan δ, RL**

• Also changes charge states of present defects (+ radiolysis)

- **Displacement** ⇨ **Point Defects**

(PERMANENT)

⇩

Clusters

⇩

Dipolar losses, ΔConductivity
Optical Absorption, Photo-Luminescence,
ΔThermal Cond., Swelling…

⇧

- **Transmutation =** **Impurities + Intrinsic Defect**

(PERMANENT)

Dose rate (flux) and dose (fluence) effects

Some of the induced changes will be dose rate dependent

---> problem from on-set of operation

others will be modified by the total dose

---> affect the component or material lifetime

The special case of insulators

Insulators are in general polyatomic materials
Hence response is more complex than in metals --->

2 or more sublattices --> may not tolerate mixing

Hence more types of defects

Defects may have different charge states and mobilities

Displacement rates and thresholds may be different on each sublattice

Interaction between defects on different sublattices

Defects produced in some cases by ionization (radiolysis)

Insulator sensitivity to radiation

Result ===> insulators are far more sensitive to radiation damage than metals

Stainless steel can withstand many dpa and GGy

But insulators can be modified by 10^{-6} dpa or a few kGy

Effect on insulator properties

All the following insulator properties are affected:

- Electrical conductivity
- Dielectric loss
- Permittivity
- Optical absorption (+ emission)
- Thermal conductivity
- Mechanical properties

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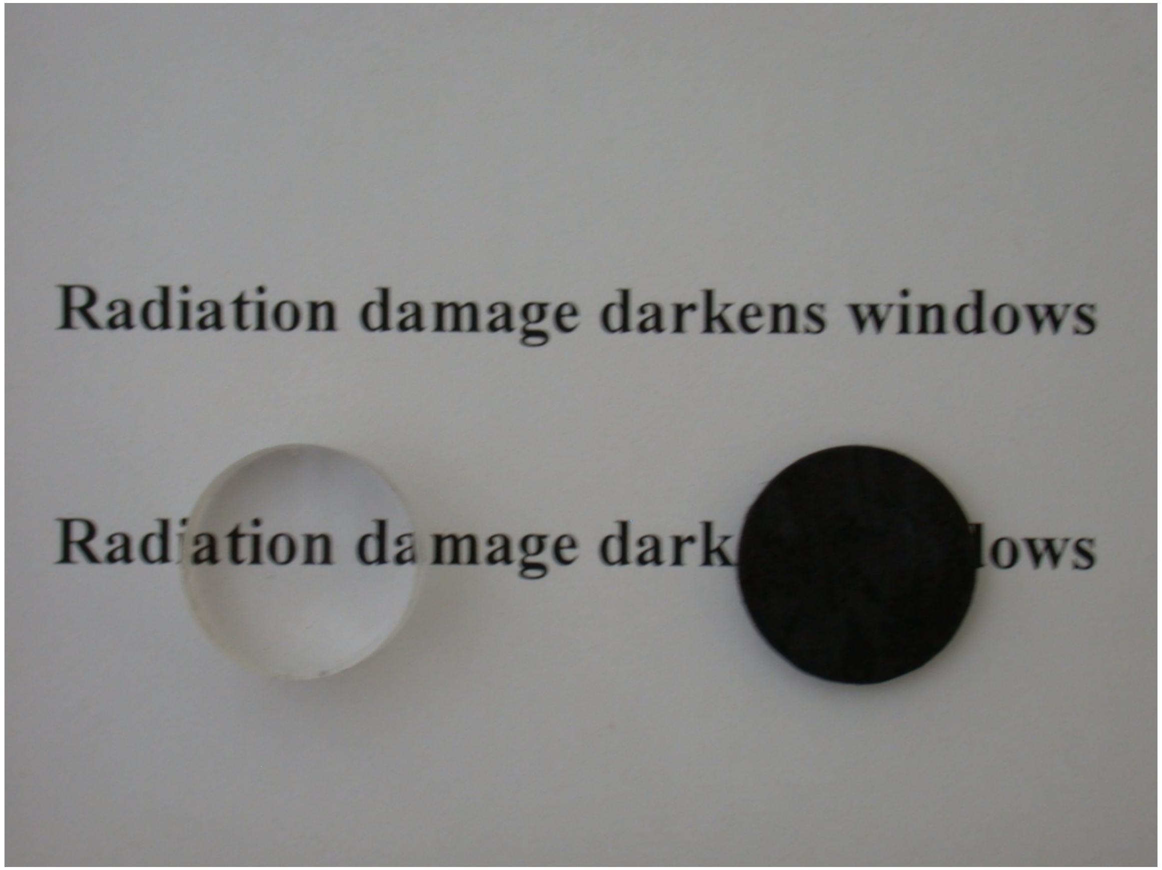
EXAMPLES

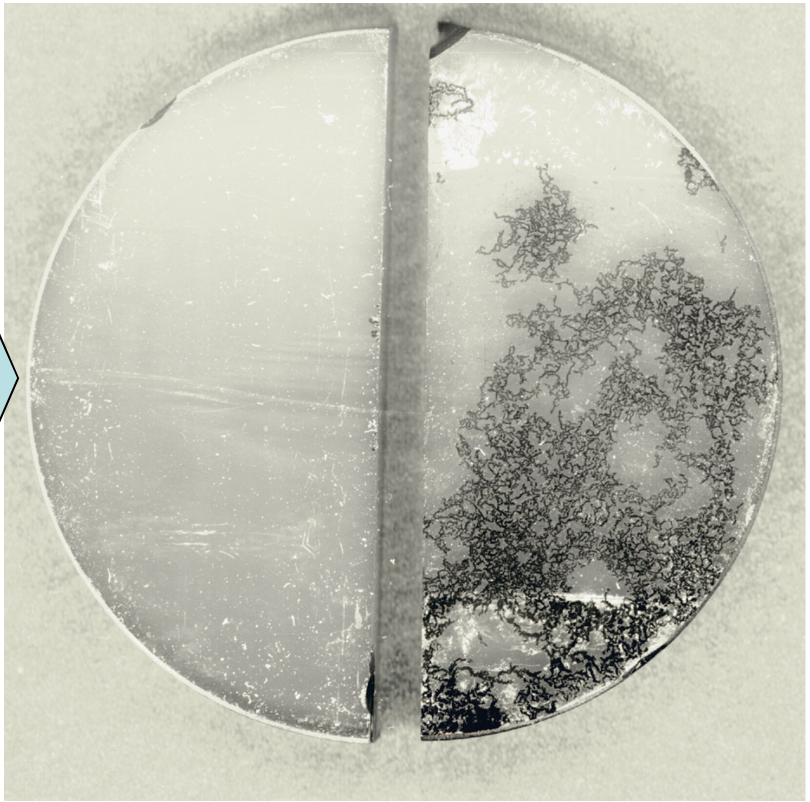
Optical transmission components: Windows and fibres become dark



Corrosion is enhanced

Radiation enhanced effects can be serious:

- Mirrors can corrode
- Even with SiO protection
- Problem for LOCA (loss-of-coolant accident)



Historical radiation damage studies

Study of <u>intense</u> radiation effects in metals --->

Associated with development of nuclear fission reactors

Hence by 1980's considerable knowledge and expertise

<u>This was not the case for the insulating materials</u>

Candidate and reference materials

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Candidate materials

- **Structural:**
  SS-316L-IG, RAFM (EUROFER, F82H), SiC, ODS

- **High heat flux:**
  W, Be, CFC on Cu (CuAl25-IG or DS Cu).

- **Breeder:**
  Liquids; Li, PbLi,   Solids; Li_2O, Li_4SiO_4, $LiAlO_2$

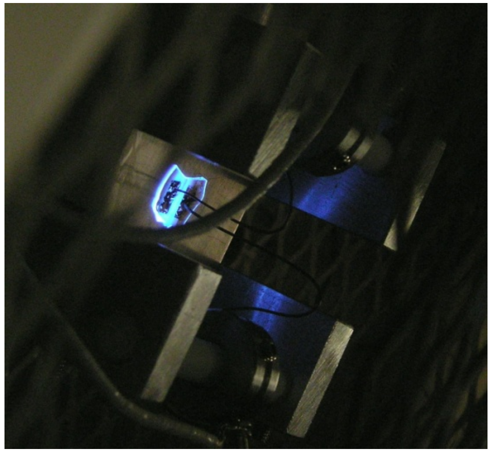
- **Cooling:**
  H_2O, He, PbLi, Li

- **Insulators (Functional):**
  Al_2O_3, MgO, BeO, $MgAl_2O_4$, AlN, Si_3N_4,SiC, SiO_2, Diamond, Silica based fibers

- ***Tritium Breeder* :**
  Liquids; Li, Li-Pb,
  Solids; Li_2O, Li_4SiO_4, $LiAlO_2$…

Insulators degradation under radiation. An example:

Behaviour of insulating materials surface under irradiation



Surface bombardment of insulators in Fusion reactors

The effect of the **bombardment of insulators surface. Interaction of charged particles with matter will be studied:**

↳ **Ions**
- **Ionization / Electronic excitation** ⇨ **EXCITON generation**
- **Nuclear collisions**

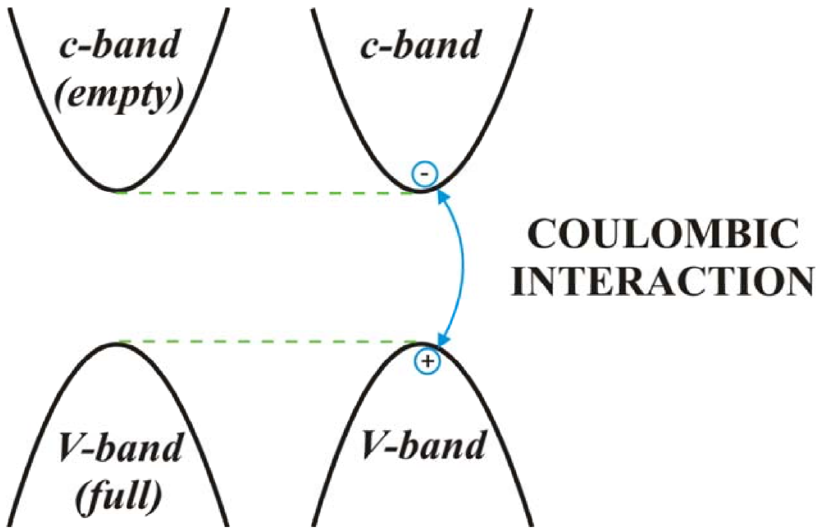
↳ β
- **Ionization / Electronic excitation** ⇨ **EXCITON generation**
- Bremsstrahlung
- Nuclear collisions

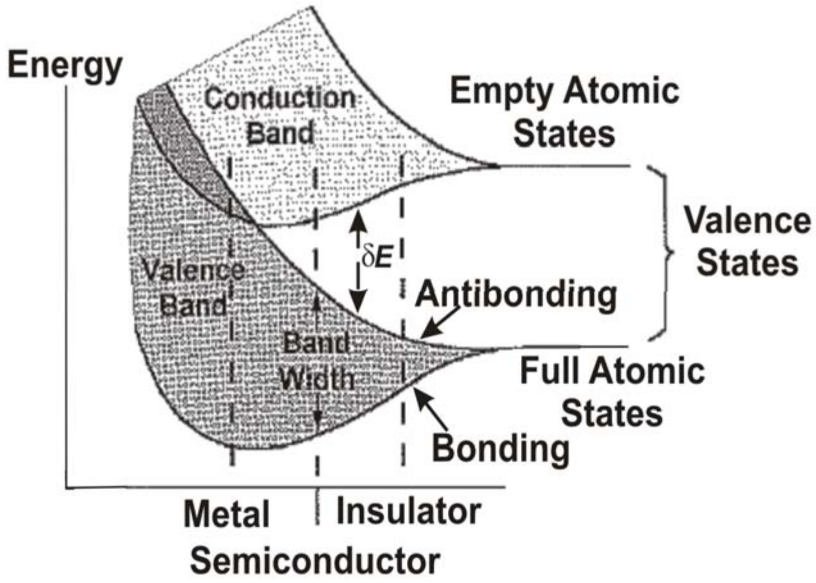
Defects produced by radiation

Ionic defects ⟶ **VACANCIES / INTERSTITIALS**

Frenkel pair: a vacancy-interstitial pair is formed when an atom is displaced from a lattice site to an interstitial site.

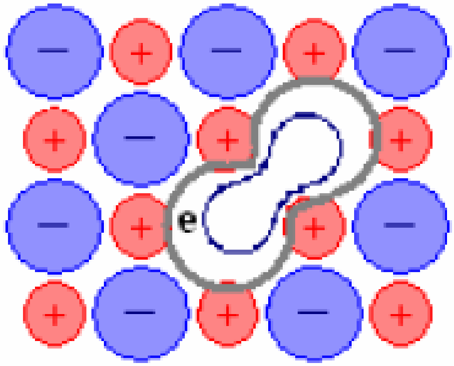
Exciton formation





Exciting an electron from the valence band into the conduction band. The missing electron in the valence band leaves a hole behind, of opposite electric charge, to which it is attracted by the Coulomb force. The exciton results from the binding of the electron with its hole; as a result, the exciton has slightly less energy than the unbound electron and hole

2.2.1 Exciton generation in Alkali Halide



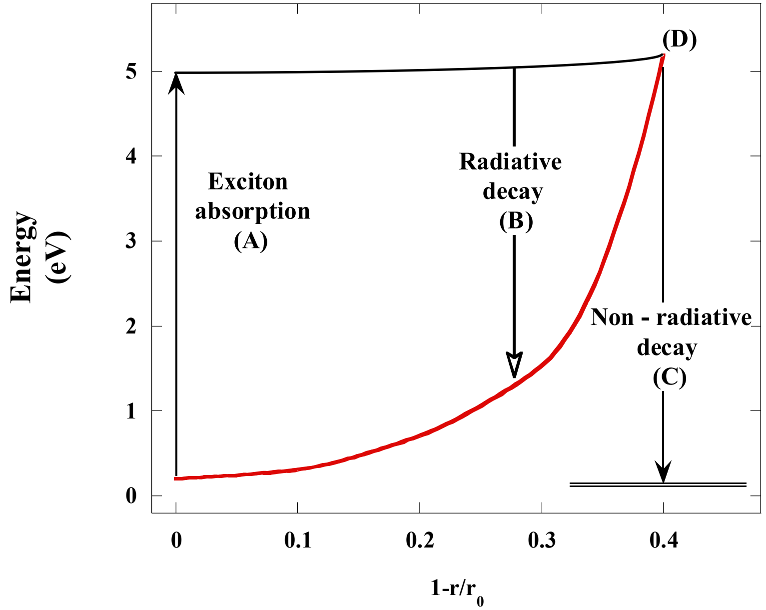
Cation

Alkali Halide: **Ionic bond**

Anion

STE: An electron trapped by Coulomb potential formed by neighboring alkali ions, and the hole is localized on two halogen ions forming a (X_2^-) molecular ion, i. e. a self-trapped hole

STE → Frenkel pair: It starts when the instability due to the Coulomb repulsion appears to induce a shift of the X_2^- molecular ion along <110> direction



Pooley Model: Exciton decay

2.3 Damage study *(i)*

Implanted & irradiated samples

Low energy particles deposit most of their energy at or very near the surface, producing high levels of ionization, atomic displacement, and sputtering. **Therefore, SURFACE DAMAGE could be produced**.

Preliminary experiments were performed in some insulators to evaluate possible optical and electrical degradation**, finding a dramatic and unexpected degradation**

2.3 Damage Study *(ii)*

Implanted & irradiated samples

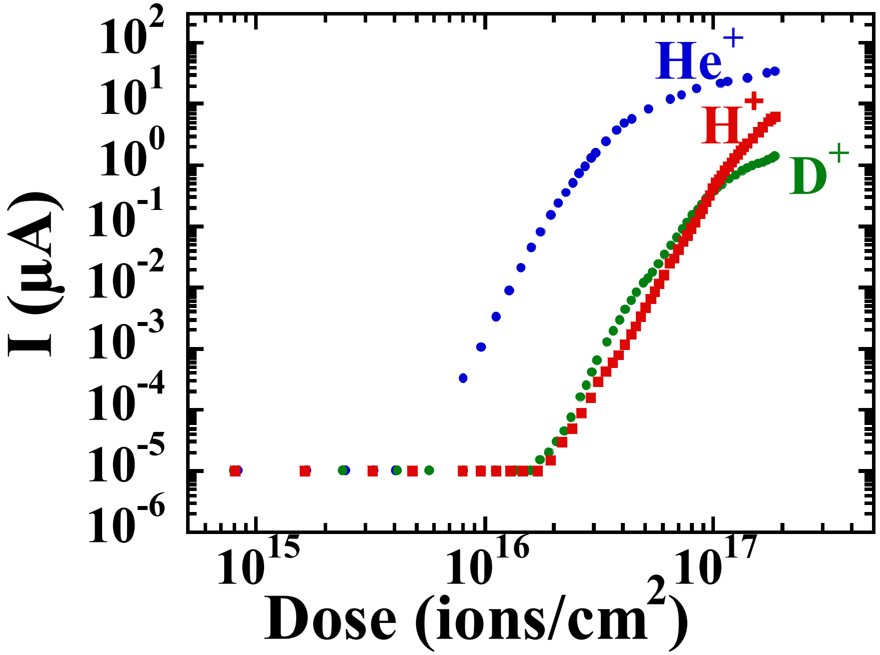
A SYSTEMATIC STUDY was carried out to assess the behaviour of the studied materials and to find the mechanisms responsible for the surface degradation

Radiation	Parameters	Material
Light ions	Dose rate	KS4V
	Energy	KS4V
	Mass	KS4V
	Temperature	KS4V, Sapphire
	Material	KS4V, Sappire, AlN, BeO
e^-	Material	KS4V, Sapphire

Measurements of superficial electrical current and optical absorption were carried out on samples implanted with light ions and irradiated with electrons

2.3.1 Damage study: implantation *(i)*

KS4V different ions implantation



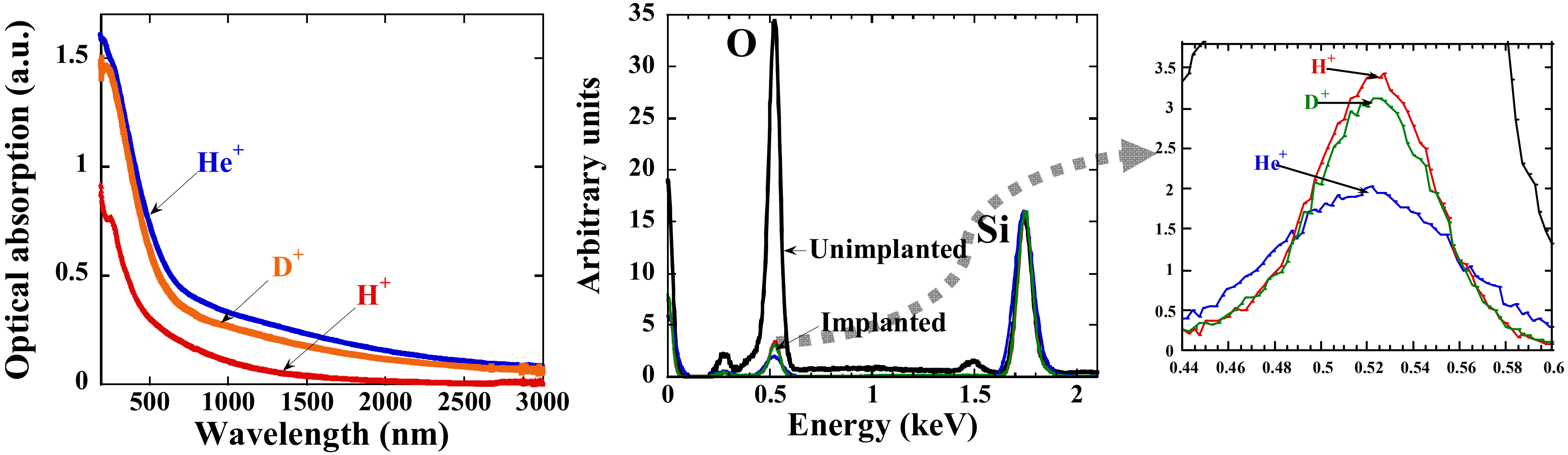
ión	Mass (a.m.u.)	dE/dx (keV/µm)
He^+	4	142.8
D^+	2	103.0
H^+	1	125.1

-A higher rate of energy deposition (dE/dx) implies a higher electrical surface degradation, independently of implanted ion mass

- The current increase begins to saturate early for higher mass ions

2.3.1 Damage study: implantation *(ii)*

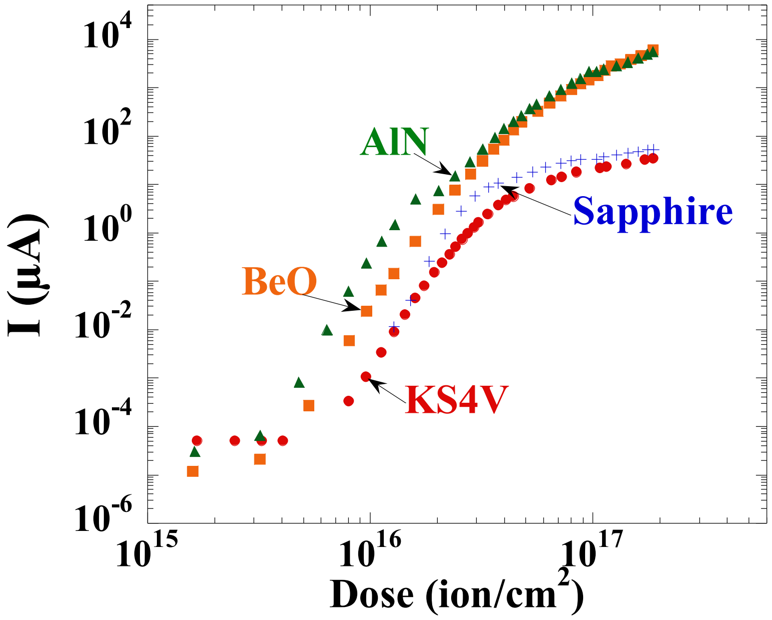
Optical and SEM measurements

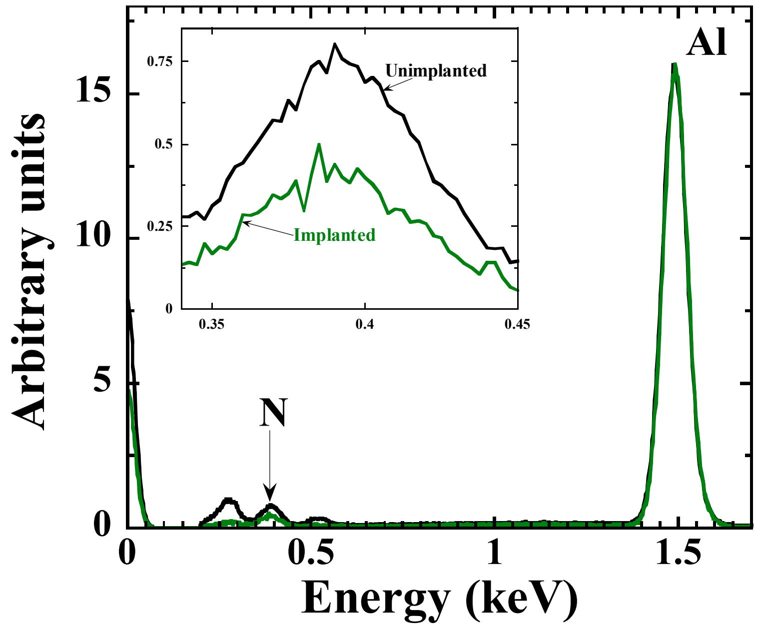


- Optical degradation is higher for heavier implanted ions. This fact is connected with a higher oxygen loss

2.3.1 Damage study: implantation *(iii)*

Different insulator material





Electrical surface degradation occurs not only in oxides, but in other insulator materials too

Not only oxygen ions are affected by radiolytic sputtering. **The anion is affected by radiolytic sputtering due to electrostatic reasons**, independently of its mass

2.3.1 Damage study: irradiation *(i)*

Irradiated materials

KS4V and **Sapphire** samples were irradiated in order to assess the rate of degradation or even if degradation occurs or not during electron irradiation.

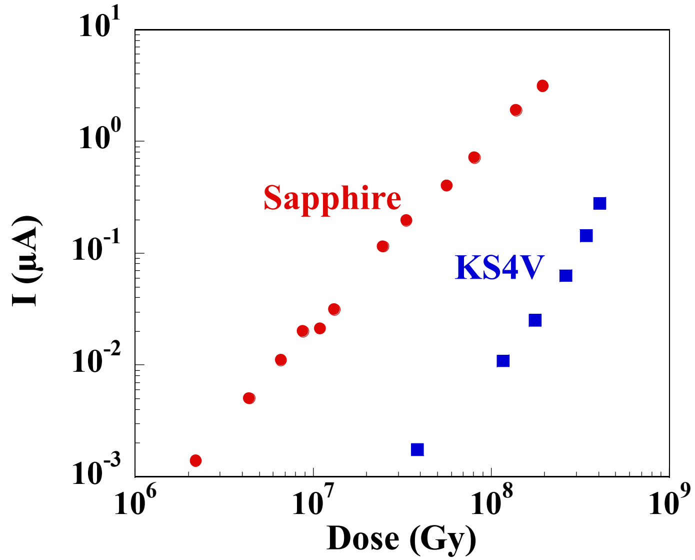
Silica → **Radiolytic processes giving rise to oxygen vacancy production occur within the bulk**

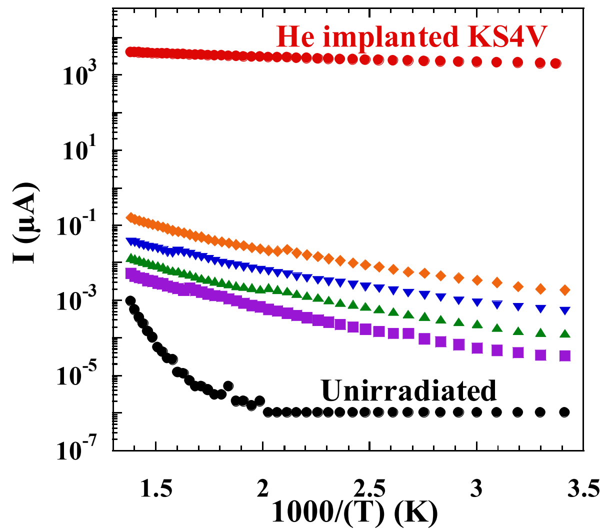
Sapphire → **Such processes do not occur, knock-on collisions are necessary to produce oxygen displacements**

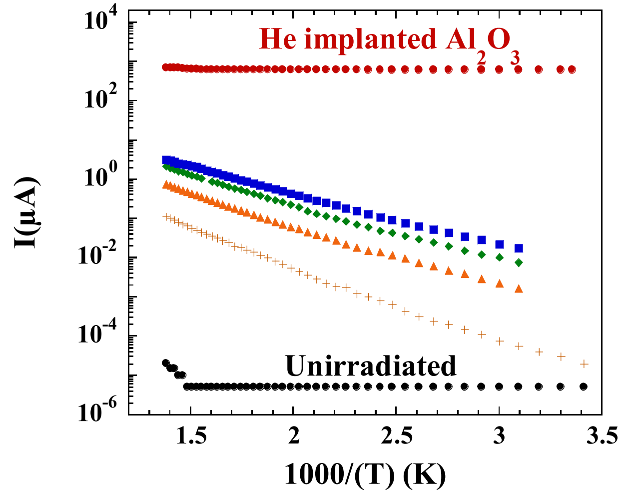
All samples were irradiated with 1.8 MeV electrons at 450ºC using the CIEMAT Van de Graaff Accelerator

2.3.1 Damage study: irradiation *(ii)*

Irradiated materials





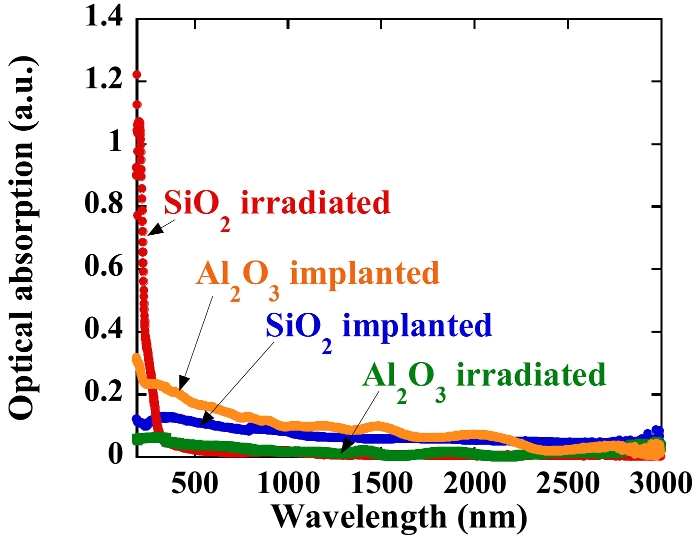


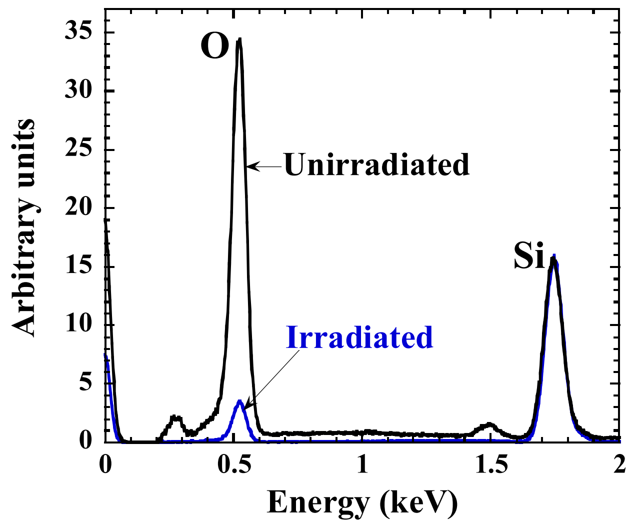
The same behaviour has been observed for the two types of oxides studied: Surface electrical degradation

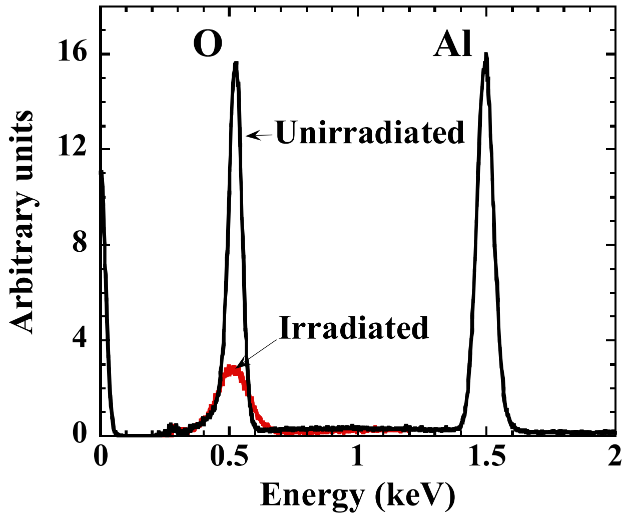
Similar surface electrical and optical degradation processes have been observed for ion implanted and electron irradiated samples

2.3.1 Damage study: irradiation *(iii)*

Irradiated materials







Oxygen removal from the irradiated surface indicates that the origin of such oxygen preferential sputtering is the ionizing radiation rather than ion displacements due to the knock-on collisions

Summary of results

The obtained results show **similar behaviour** in all studied cases, for **implanted samples as well as for irradiated ones**:

- *Electrical surface degradation appears after a certain dose*
- *X ray analysis carried out after irradiation (with electrons or ions) shows a dramatic loss of the anion element in the irradiated region*
- *The loss of the most electronegative element is related to a reduction in the material band gap*
- *Curves of superficial electrical current as a function of temperature exhibit a low activation energy, suggesting electronic rather than ionic conductivity*

All these facts indicate **the existence of a mechanism** by which the anion is removed from the material's surface

Damage explanation (i)

RADIOLYTIC SPUTTERING MECHANISM

The proposed mechanism is based on these three main points:

- ***Damage on superficial layers is mainly generated by excitonic mechanism, via non radiative recombination of STE***
- ***STEs may diffuse from the bulk to the material surface, following an adiabatic potential, carrying energy, and therefore, being able to generate damage far from where the electronic excitation was produced***
- ***Surface processes are affected by an anti-bonding superficial potential, which exists in all materials (metals, insulators and semiconductors). This potential was postulated by Menzel and Gomer, and Redhead (MGR) to explain the surface desorption, even when direct transfer of momentum is not energetic enough to be able to produce it***

From the last point, a very important consequence is derived: The energy needed to break bonds on the surface of all studied materials is only a few eV, which means that, although breaking bonds is not possible into the material bulk (tens of eV or higher), it is possible on the surface

Conclusions – Surface damage

- **Unexpected Surface degradation was observed in all the studied materials**

- The results show that the **origin of the damage and the associated physical mechanisms are the same: radiolytic**, i.e. the damage is caused by the electronic excitation induced during material irradiation

- The surface electrical conductivity is due to a loss of the anion by **radiolytic sputtering**, and the consequent reduction in the band gap width in the material damage zone

- **Importance of surface bombardment processes and their relevance from a technological point of view**

Final conclusions

- The nature of non- metallic materials makes them highly sensitive to both ionization and displacement damage, with the result that the properties of interest may be severely modified even at low dose rates and for low doses.
- Insulators are far more sensitive to radiation damage than metals
- Insulator materials are critical components of a number of different systems: RF window, NBI, cables, wires, etc. employed in many diagnostic and remote handling systems
- Candidate materials: Al_2O_3, MgO, BeO, $MgAl_2O_4$, AlN, Si_3N_4,SiC, SiO_2, Diamond, Silica based fibers

Thank you for your attention!

Courtesy of C. Alejaldre