Radiation Effects in Solids after High Energy Electron Irradiation

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NATIONAL SCIENCE CENTER
Kharkov Institute of Physics & Technology
“CYCLOTON” Science & Research Establishment
Kharkov, Ukraine
Found – in 1928
Staff: 2500
Accelerators: more then 15
Stellarators: "Uragan-3M", “Uragan-2M”

Institutes:
• Institute of Solid State Physics, Materials Science & Technologies
• Institute of High-Energy Physics & Nuclear Physics
• Institute of Plasma Physics
• Institute of Plasma Electronics & New Methods of Accelerating
• Institute of Theoretical Physics
“CYCLOTON” Science & Research Establishment
(Center of joint use of accelerator facilities)

Basic facilities:
• ELIAS electrostatic accelerator
  (High Voltage Corporation, USA)
• Compact Cyclotron CV-28
  (The Cyclotron Corporation of Berkeley, USA)
Outline:

• Effect of point defects on critical current of high-$T_c$ superconductors

• Point defects and recovery kinetics in irradiated bulk metallic glasses

• Defect production and recovery process in zirconium-based alloys

• The role of defects in the electronic transport in thin-film silicon

• Compact Cyclotron CV-28: Present and future
“ELIAS” electrostatic accelerator of electrons
as precise generator of point-like defects in solids

Parameters: Energy of electron beam 0.5 - 3.0 MeV
Beam current 1 - 500 mkA
“ELIAS” accelerator’s output facility (cryostat for irradiation)
• Effect of point defects on critical current of high-$T_c$ superconductors

Question:
Whether point defects are effective pinning centers in high-$T_c$ superconductors?

• STCU Projects #655, #655A
Experimental

Samples: High-quality YBaCuO single crystals, $T_c \approx 93$ K.

Irradiation: 2.5 MeV electrons in a liquid helium cryostat at temperatures $T \leq 10$ K at doses up to $3 \times 10^{18}$ el/cm$^2$.

temperature range for operation from 10 to 400 K.

magnetic field up to 6T.

accuracy of temperature control and regulation 0.003 K.

a goniometric sample holder to rotate the crystals with respect to the vector of the magnetic field.

Technique: Current-voltage characteristics measured by dc-resistivity method.
$YBa_2Cu_3O_{7-x}$ single crystal

$H = 1.5 \, T$, $Ft = 3.1 \times 10^{18} \, \text{el/cm}^2$

Irradiation with 2.5 MeV electrons at 10 K
**YBa$_2$Cu$_3$O$_{7-x}$ single crystal**

$T=77$ K, $\text{angl}_{H_{ab}}=14^\circ$, $H=1.5$ T

![Graph showing fluence vs. current density](image)
**YBa$_2$Cu$_3$O$_{7-x}$ single crystal**

$H = 1.5\, T$, angle$_{ab} = 14^\circ$

![Graph showing current density vs. temperature for YBa$_2$Cu$_3$O$_{7-x}$ single crystal with specified conditions.](image-url)
YBa$_2$Cu$_3$O$_{r-x}$ single crystal

$T = 85$ K, $\text{angle}_{\text{Hab}} = 14^\circ$
$YBa_2Cu_3O_{7-x}$ single crystal irradiated with 2.5 MeV electrons at 10K

$H = 1.5 \, T$, angle $\theta_{ab} = 14^\circ$
**YBa\textsubscript{2}Cu\textsubscript{3}O\textsubscript{7-x} single crystal**

$H = 1.5$ T, $T = 81$ K

Irradiation with 2.5 MeV electrons at $10$ K
Conclusions:

It has been first demonstrated that point defects generated by the ~MeV electron beam are the effective pinning centers of magnetic vortices in high-$T_c$ crystals, and this determines a substantial rise in the critical current density in irradiated superconductors.
“ELIAS” Accelerator

• Point Defects and Recovery Kinetics in Irradiated Bulk Metallic Glasses

• Yu. Petrusenko, A. Bakai et al., Intermetalics 17 (2009) 246.
The problem of structural properties and structural defects of amorphous solids is still of vital importance.

To make clear whether stable point defects exist in metallic glasses (MGs), we have studied the accumulation and recovery kinetics of radiation defects in ZrTiCuNiBe and ZrTiCuNiAl bulk MGs irradiated with 2.5 MeV electrons at T ~ 80 K.
Experimental:

- **The method:**
  - low-temperature electron irradiation
  - isochronal annealing
  - electrical resistance measurements

- **Samples:**
  - amorphous alloys, $\text{Zr}_{41}\text{Ti}_{14}\text{Cu}_{12.5}\text{Ni}_{10}\text{Be}_{22.5}$
  - $\text{Zr}_{52.5}\text{Ti}_{5}\text{Cu}_{17.9}\text{Ni}_{14.6}\text{Al}_{10}$,
  - 0.05 mm in thickness, prepared by the spinning method

- **Irradiation:**
  - 2.5 MeV electrons at ELIAS electrostatic accelerator
  - Maximal exposed dose $7.5 \times 10^{19} \text{ e}^-/\text{cm}^2$
  - Temperature of irradiation $T_{\text{irr}} \sim 80 \text{ K}$.

- **Isochronal annealing:** temperature range 85-300 K, 10 K step

- **Electrical resistance measurements:** at $T= 80.5 \text{ K}$ by precise fore-probe method, accuracy - 5 ppm
Dose dependences of relative electrical resistance for ZrTiCuNiBe and ZrTiCuNiAl irradiated with 2.5 MeV electrons at 85 K.
Recovery of irradiation-induced resistance of ZrTiCuNiBe irradiated with 2.5 MeV electrons at 85 K to dose $7.5 \times 10^{19}$ e-/cm$^2$. 
Recovery spectrum of irradiation-induced resistance for ZrTiCuNiBe irradiated with 2.5 MeV electrons at 85 K to dose $7.5 \times 10^{19}$ e-/cm$^2$. 
Effective activation energies of recovery stages for ZrTiCuNiAl and ZrTiCuNiBe bulk metallic glasses irradiated with 2.5 MeV electrons

(Estimated data)

• ZrTiCuNiBe:
  
  \[ E_{150K} = 0.46 \text{ eV} \]
  
  \[ E_{225K} = 0.69 \text{ eV} \]

• ZrTiCuNiAl:
  
  \[ E_{135K} = 0.40 \text{ eV} \]
  
  \[ E_{225K} = 0.69 \text{ eV} \]
Polycluster amorphous structures
A. S. Bakai, Polycluster amorphous solids. – Moscow: Energoatomizdat (1987)

A fragment of the 2-D polycluster
Intercluster and inner boundaries are shown:
• -regular sites;
circles with dot are coincident sites;
semicircles with dot are noncoincident sites
Subcluster structure of the Zr–Ti–Cu–Ni–Be BMG


Field ion microscopic images of the V-01 BMG after pulsed field evaporation at a rate about 1 nm/s (a) and hydrogen promoted field etching (b).

![Field ion microscopic images](image-url)
Conclusions:

• Point defects are stable in metallic glasses and the defect mobility is a thermally activated process.
• Activation energies of recovery processes in metallic glasses are lower than migration energy of vacancies in crystals.
• Intercluster boundaries are the most probable sinks of the point defects.
• Structural model of densely random-packed spheres or free volume model is irrelevant to bulk metallic glasses.
• The results are in accord with the polycluster structure of bulk metallic glasses.
• It is reasonable to predict high radiation tolerance of bulk metallic glasses.
“ELIAS” Accelerator

• The role of defects in the electronic transport in thin-film silicon

• STCU Projects #655A, #P332, #P429
a-Si:H and μc-Si:H

Material for cheap production:
- Large area electronics
- Photovoltaics
- Photosensors
- Thin Film Transistors (TFT displays)

• Defects strongly affect the quality of devices
• In order to improve devices quality the nature of defects and their role is investigated
• Electron bombardment – a tool for the defect density manipulation
μc-Si:H – materials for solar cell, photosensors and large scale electronic device production

**FZJ-IPV**

Sample preparation

Investigation
ESR (40-300K)
Dark and photoconductivity
Spectral absorption, etc.

**NSC-KIPT**

Transportation

Irradiation

E=2МэВ е–
J=5мкА*см–2
T_іrr ~80 K
D_{max} =10^{19} e*см–2

Reloading
at 77K

Test measurements

Transportation at 77 K
Electron Spin Resonance (ESR) measurements

\[ N_s \text{ (cm}^{-3}) \]

\[ \begin{array}{cccc}
\mu\text{c-Si:H} & a\text{-Si:H} \\
10^{15} & 10^{16} & 10^{17} & 10^{18} & 10^{19} \\
\end{array} \]

Treatment

Deposited

Irradiated

50°C

80°C

120°C

160°C

ESR intensity

\[ g\text{-value} \]

Irradiated

Annealed

Deposited

2.02

2.01

2.00

1.99
Spin density $N_S$ in as-deposited material (black circles) and $N_S$ after irradiation (black stars) as a function of silane concentration ($SC=SiH_4/\text{SiH}_4+H_2$). The ratio $N_{S\text{ Irr}}/N_{S\text{ Dep}}$ is shown with triangles.
Conclusions:

• Effective use of low-temperature electron irradiation as a method of increasing the defect density in thin-film silicon without changing its microstructure.

• Elucidation of the role of defects in electron transport in the material.

• The results are of importance for improving the silicon-based thin-film device production technology.
• Primary defect production and recovery process in binary Zr-based alloys (Zr-Sc, Zr-Y, Zr-Gd, Zr-Dy, Zr-La)

Recovery of irradiation-induced resistance for Zr-based alloys irradiated with 2 MeV electrons at ~80K to dose $1.4 \times 10^{19} \text{ e-/cm}^2$.
Recovery spectrum of irradiation-induced resistance for Zr-based alloys irradiated with 2 MeV electrons at ~80K to dose $1.4 \times 10^{19}$ e-/cm$^2$. 
Conclusions:

• Alloying atoms of rare earths have been found to interact effectively with point defects in the zirconium matrix.

• The observed processes effects on annihilation and redistribution of radiation defects
Compact Cyclotron CV-28:

Present & Future

(Putting into operation – 2011)
Switching magnet
## Compact Cyclotron CV-28

<table>
<thead>
<tr>
<th>Particles</th>
<th>Beam Energy Range</th>
<th>External Current at Minimum Energy</th>
<th>External Current at Maximum Energy</th>
<th>Internal Current</th>
</tr>
</thead>
<tbody>
<tr>
<td>H⁺</td>
<td>2 – 24 MeV</td>
<td>70 мкА</td>
<td>70 мкА</td>
<td>500 мкА</td>
</tr>
<tr>
<td>D⁺</td>
<td>3 – 14 MeV</td>
<td>100 мкА</td>
<td>100 мкА</td>
<td>500 мкА</td>
</tr>
<tr>
<td>³He⁺⁺</td>
<td>5– 36 MeV</td>
<td>15 мкА</td>
<td>70 мкА</td>
<td>150 мкА</td>
</tr>
<tr>
<td>⁴He⁺⁺</td>
<td>8 – 28 MeV</td>
<td>10 мкА</td>
<td>50 мкА</td>
<td>100 мкА</td>
</tr>
</tbody>
</table>
## Damage parameters for Cyclotron’s ions

<table>
<thead>
<tr>
<th>Particles</th>
<th>Max Beam Energy</th>
<th>Average Current</th>
<th>Max Dose Rate</th>
<th>Max Dose</th>
</tr>
</thead>
<tbody>
<tr>
<td>H⁺</td>
<td>24 MeV</td>
<td>50 мкА</td>
<td>~5x10⁻⁶ dpa/sec</td>
<td>~0.25 dpa</td>
</tr>
<tr>
<td>D⁺</td>
<td>14 MeV</td>
<td>50 мкА</td>
<td>~10⁻⁴ dpa/sec</td>
<td>~5.0 dpa</td>
</tr>
<tr>
<td>³He++]</td>
<td>36 MeV</td>
<td>50мкА</td>
<td>~2x10⁻⁴ dpa/sec</td>
<td>~10 dpa</td>
</tr>
<tr>
<td>⁴He++]</td>
<td>28 MeV</td>
<td>50мкА</td>
<td>~10⁻³ dpa/sec</td>
<td>~50 dpa</td>
</tr>
</tbody>
</table>
“Neutron source”

based on Compact Cyclotron CV-28
(Thick target Be source)

\[ ^9\text{Be}(d,n)^{10}\text{B} \]

D\(^+\) beam \(\rightarrow\) Be target \(\rightarrow\) \(~\text{MeV}~\text{neutrons}\)

Max Flux Density \(\sim 10^{12} \text{ n/cm}^2\text{sec} \)

Max Neutron Dose \(\sim 10^{17} \text{ n/cm}^2 \)

(for D\(^+\) Beam Energy -14 MeV, Beam Current -100 mkA)
Neutron Energy, MeV

Flux (10^6 cm^-2 s^-1 MeV^-1)

Ed=14 MeV
Neutron source

- Development of radiation-resistant magnetic field sensors
- Development and testing of neutron detectors
- Element analysis
- Neutron effects on biological materials
- etc.
WELCOME
for planning and realization of joint Projects