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Radiation-induced structure modification in monocrystalline silicon under high-energy ion irradiation

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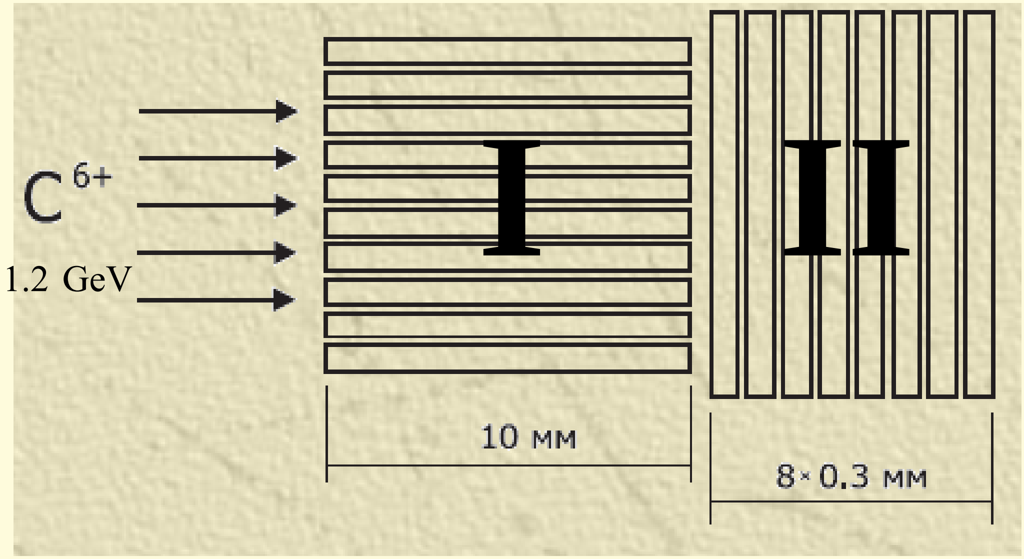
Introduction

Surface morphology and structural modification in silicon after 1.2 GeV C^{6+} and 21 MeV p^+ irradiation.

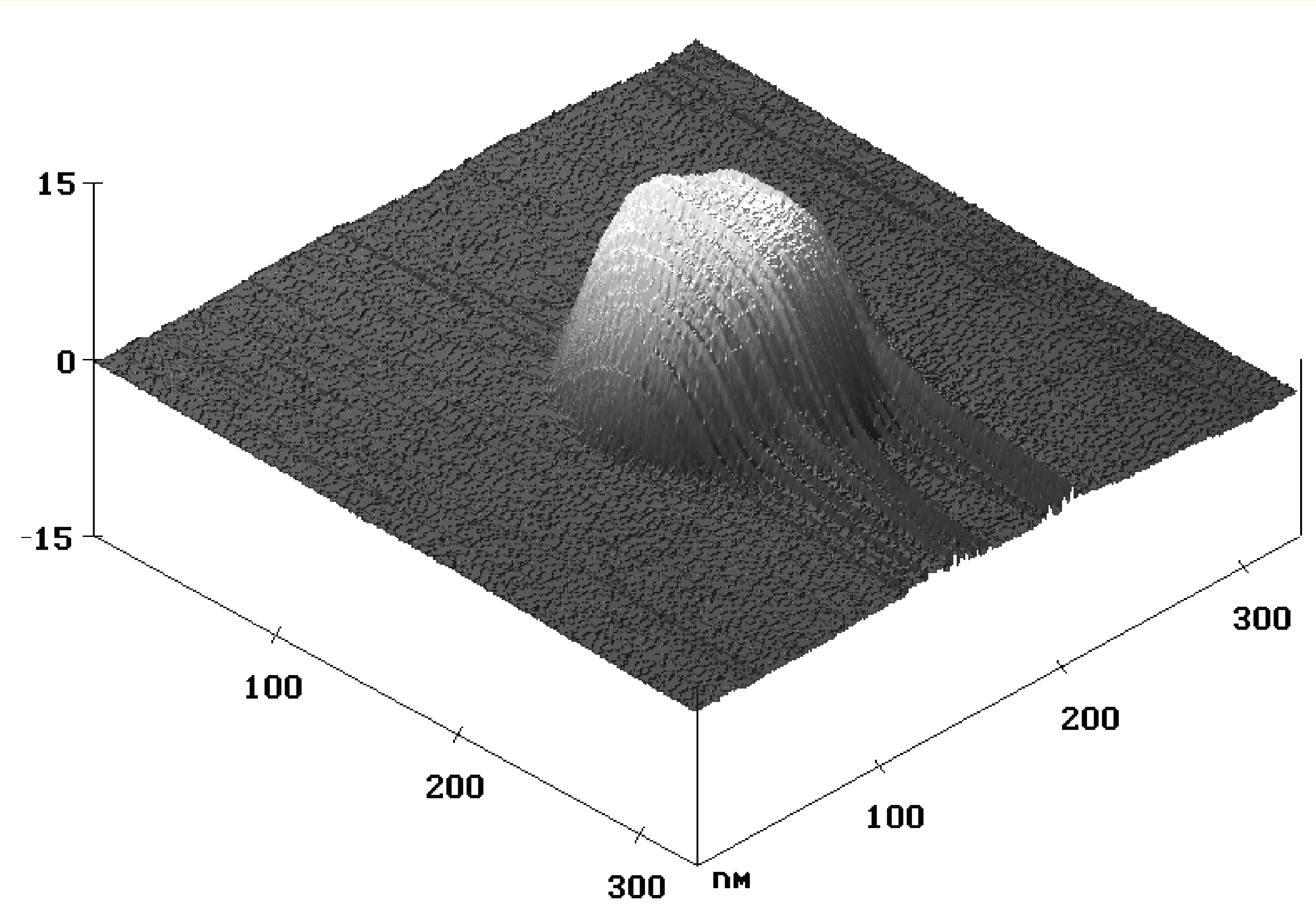
- Material: n-Si(100) kef-4.5 (ρ=4.5 Ωcm)
- Specimen size: 7x7x0.3 mm, 10x10x0.3 mm
- Ions: C^{6+}, p^+
- Fluences(cm^{-2}): $6x10^{11}$, $1x10^{12}$, $5x10^{14}$, $5x10^{15}$, $1x10^{16}$
- Temperature: room, 100-300^o C,
- AFM, XDS, XPS

Specimen irradiation

- Source parameters:
  - Ion C^{6+}
  - Energy 1.2 GeV
  - projected range (SRIM) 14.2 mm
  - Fluence = $1x10^{12}$ cm^{-2}
- assembly parameters:
  - n-Si (100)
  - thickness 0.3 mm
  - 10+8 specimens



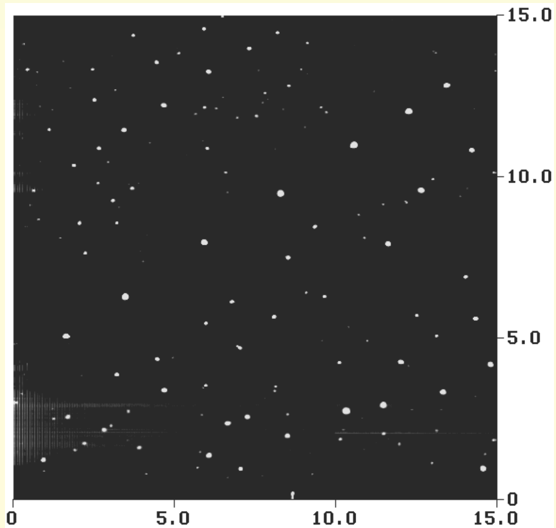
Surface morphology



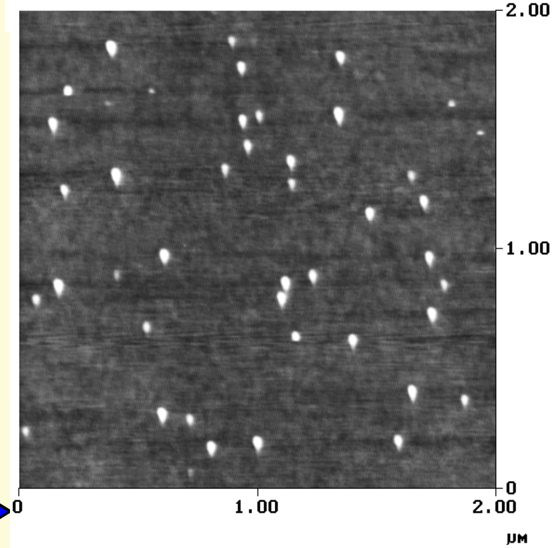
AFM image of a hillock

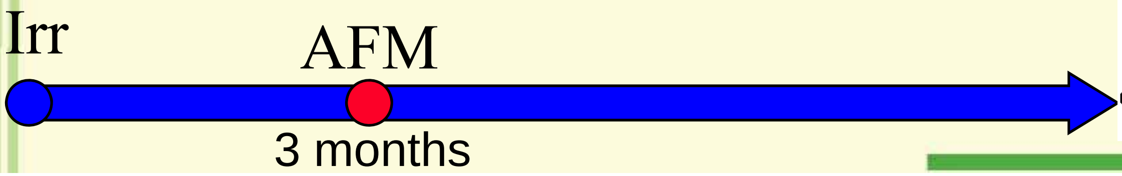
Surface morphology

- specimens of type I (placed parallel to the beam)
  - hillocks form long straight lines
  - $d = 100 \pm 10$ nm
  - $h = 2\text{-}4$ nm

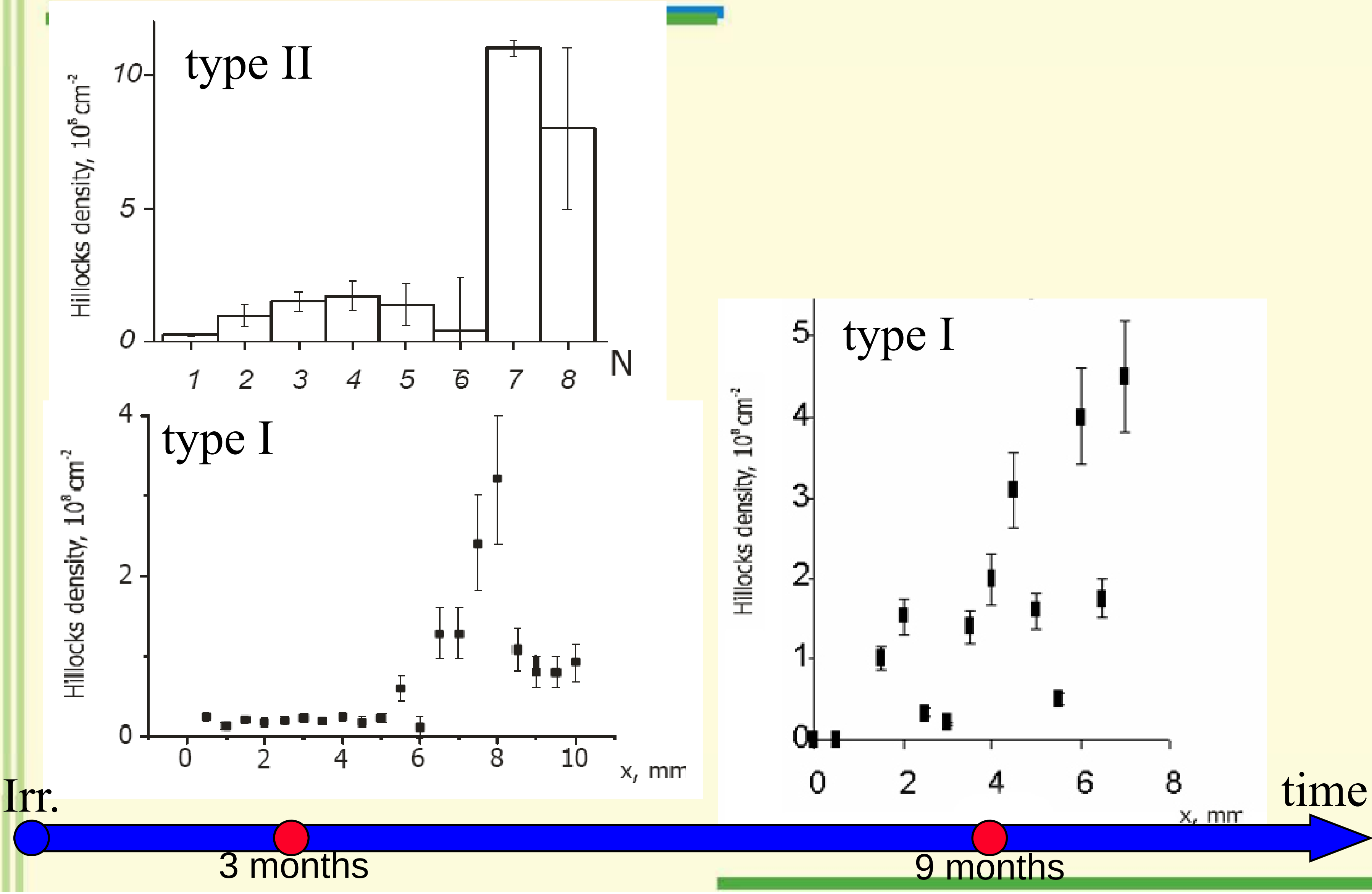


- specimens of type II (placed perpendicular to the beam)
  - hillocks placed randomly
  - $d = 200 \pm 50$ nm
  - $h = 2\text{-}4$ nm

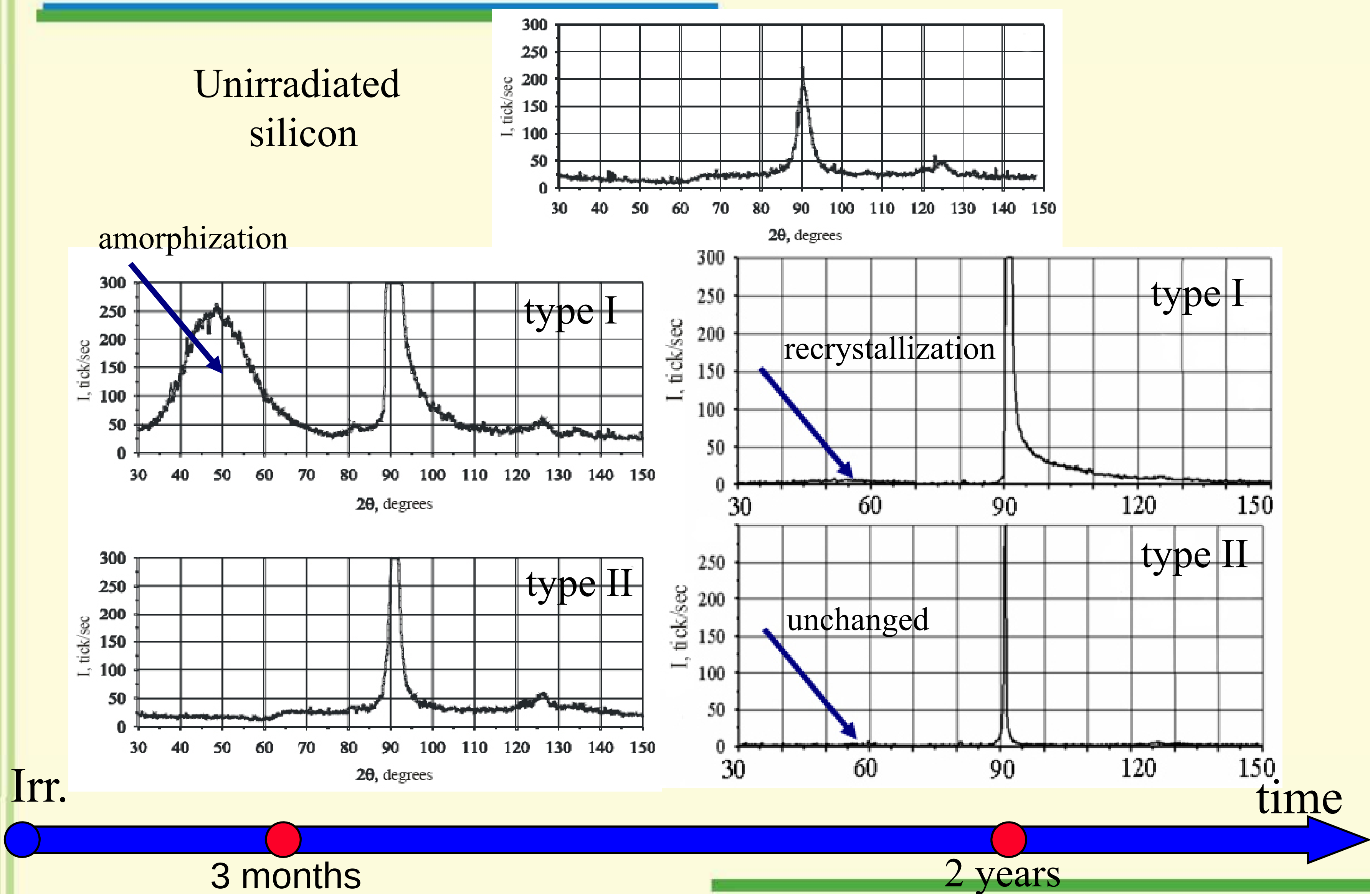




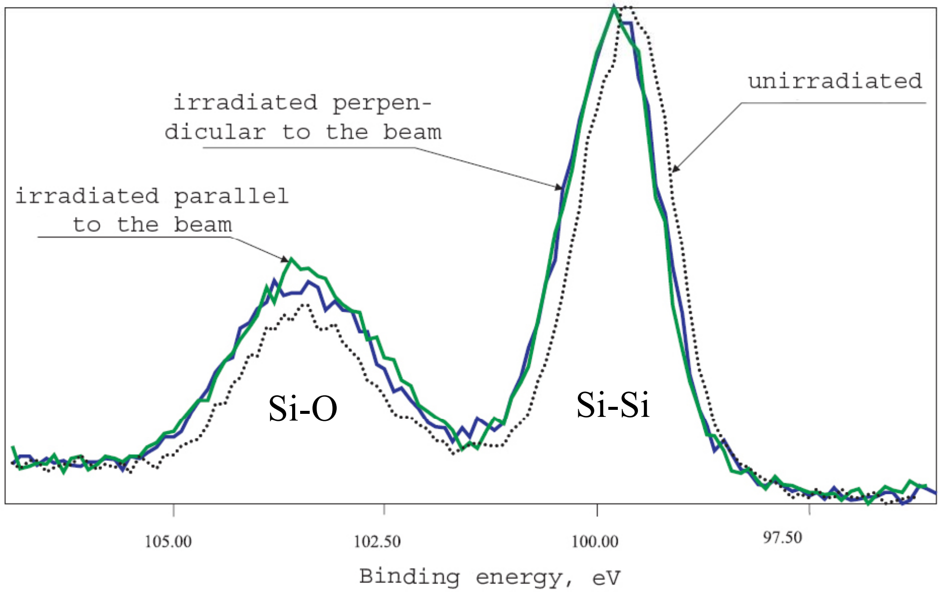
Distribution of hillocks number density versus ion penetration depth



X-Ray Diffraction



X-Ray Photoelectron Spectroscopy (XPS)

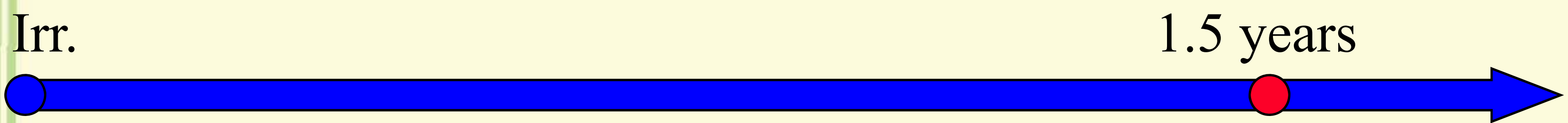


Uncompensated charge in bulk Si dissolves after irradiation

Increasing of oxidized silicon concentration

Results

– hillocks consists of oxidized silicon
– hillocks properties are the same (different ion energies)



Intermediate conclusions

✓After irradiation a number of hillocks emerged on the surface.

✓Hillocks density increases with time.

✓If the ion beam is perpendicular to the specimen plane, only surface defects were found (no amorphization), but in the case of a parallel beam both changes in a surface and bulk can be observed.

✓In a year amorphization dissolves (re-crystallization occurred)

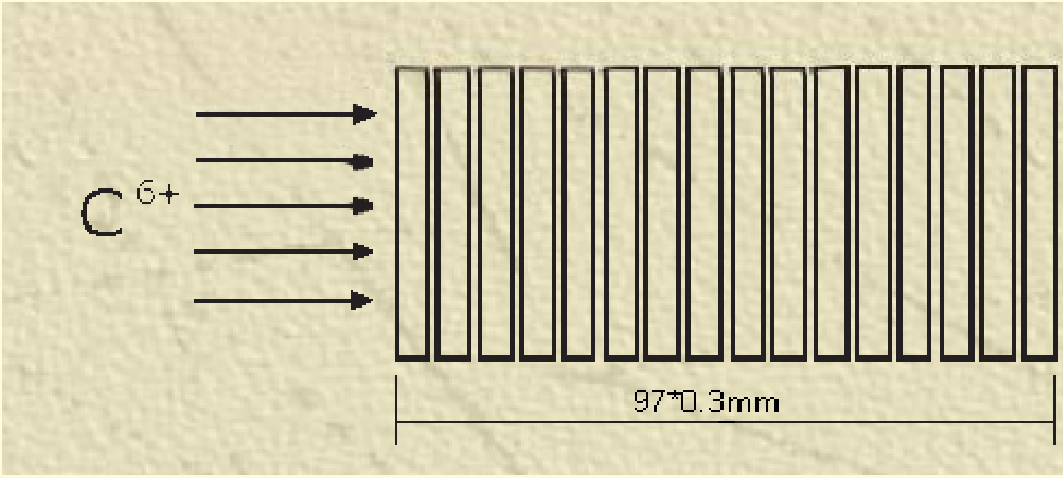
✓Nature of hillocks (oxides)

➢Arisen questions:

- ➢Influence of irradiation parameters (energy, fluence) on hillocks formation
- ➢The role of temperature in hillocks formation.
- ➢Typical hillocks nucleation time
- ➢The role of “tracks” in hillocks formation

Second experiment

- Source parameters:
  - Ion C^{6+}
  - Energy 1.2 GeV
  - projected range 14.2 ± 0.6 mm (approximately 47 plates)
  - Fluence = 6×10^{11} cm^{-2}
- Assembly parameters:
  - n-Si (100)
  - thickness 0.3 mm
  - 97 perpendicular specimens

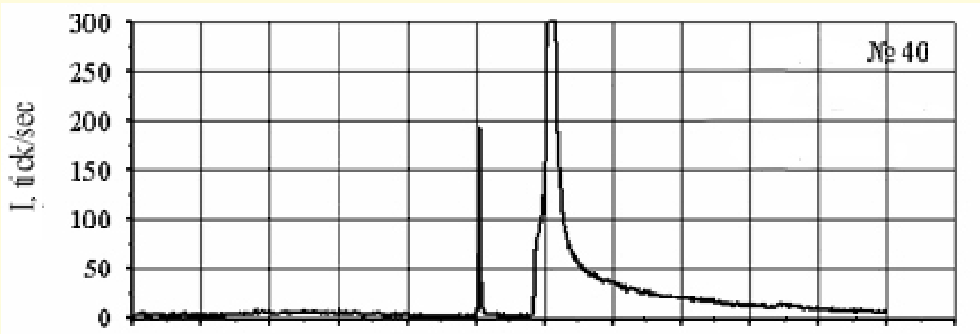


Surface morphology disturbance

Specimens placed perpendicular to the beam

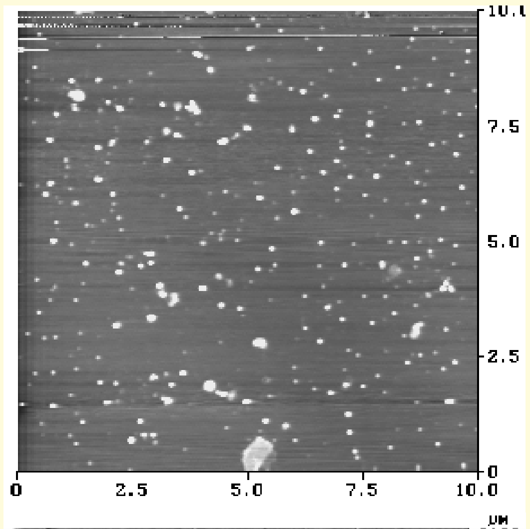
- hillocks
  - randomly placed
  - $d = 100$ нм
  - $h = 8\text{-}10$ нм
  - $n = 2x10^9$ cm^{-2}

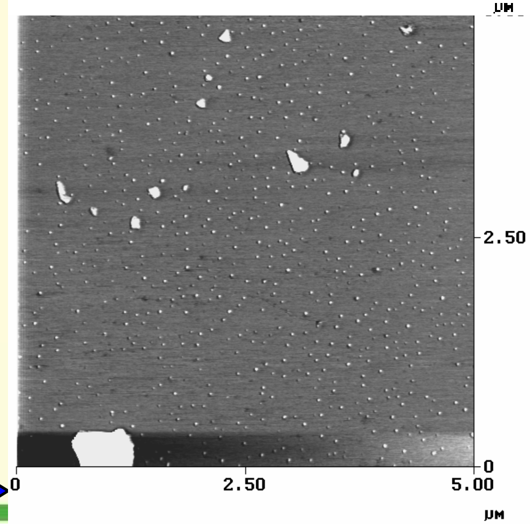
•no amorphization occurred



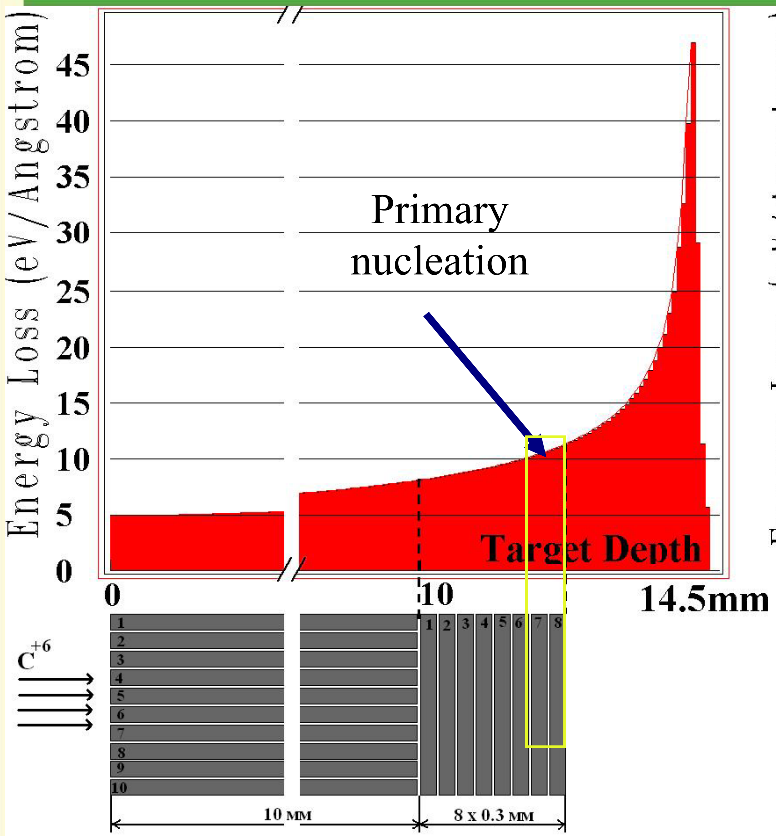
8 month

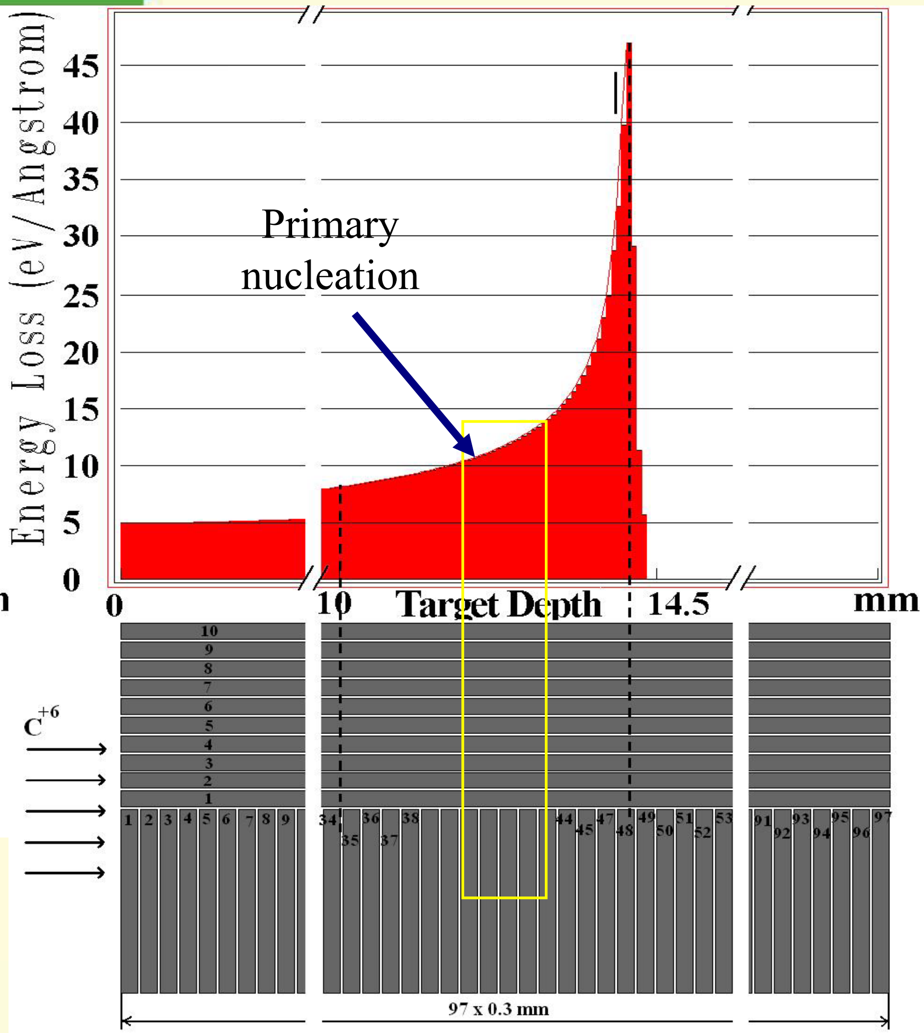
time





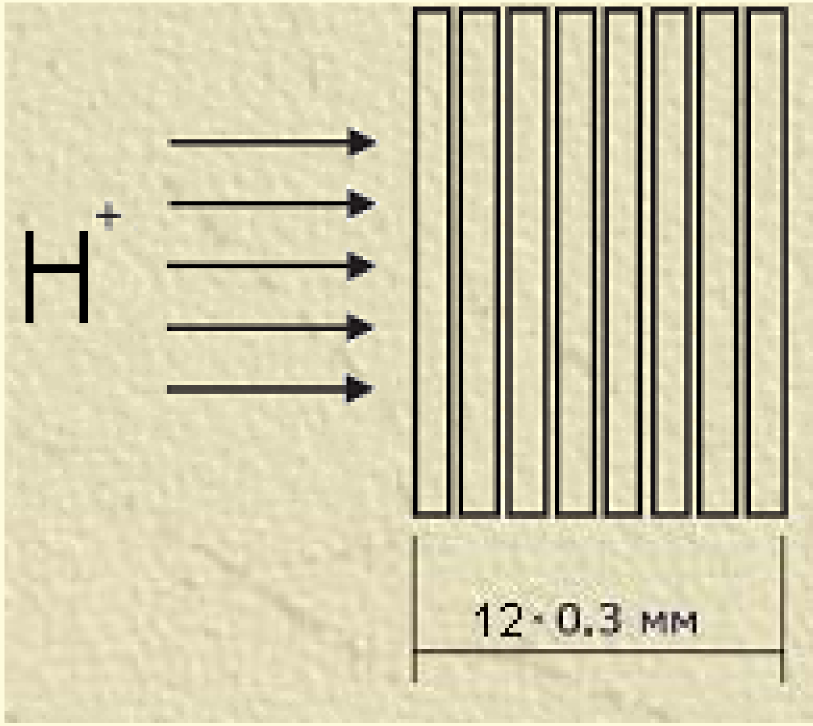
Comparison of two experiments

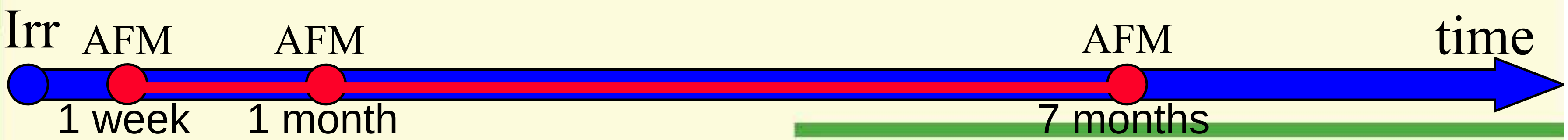




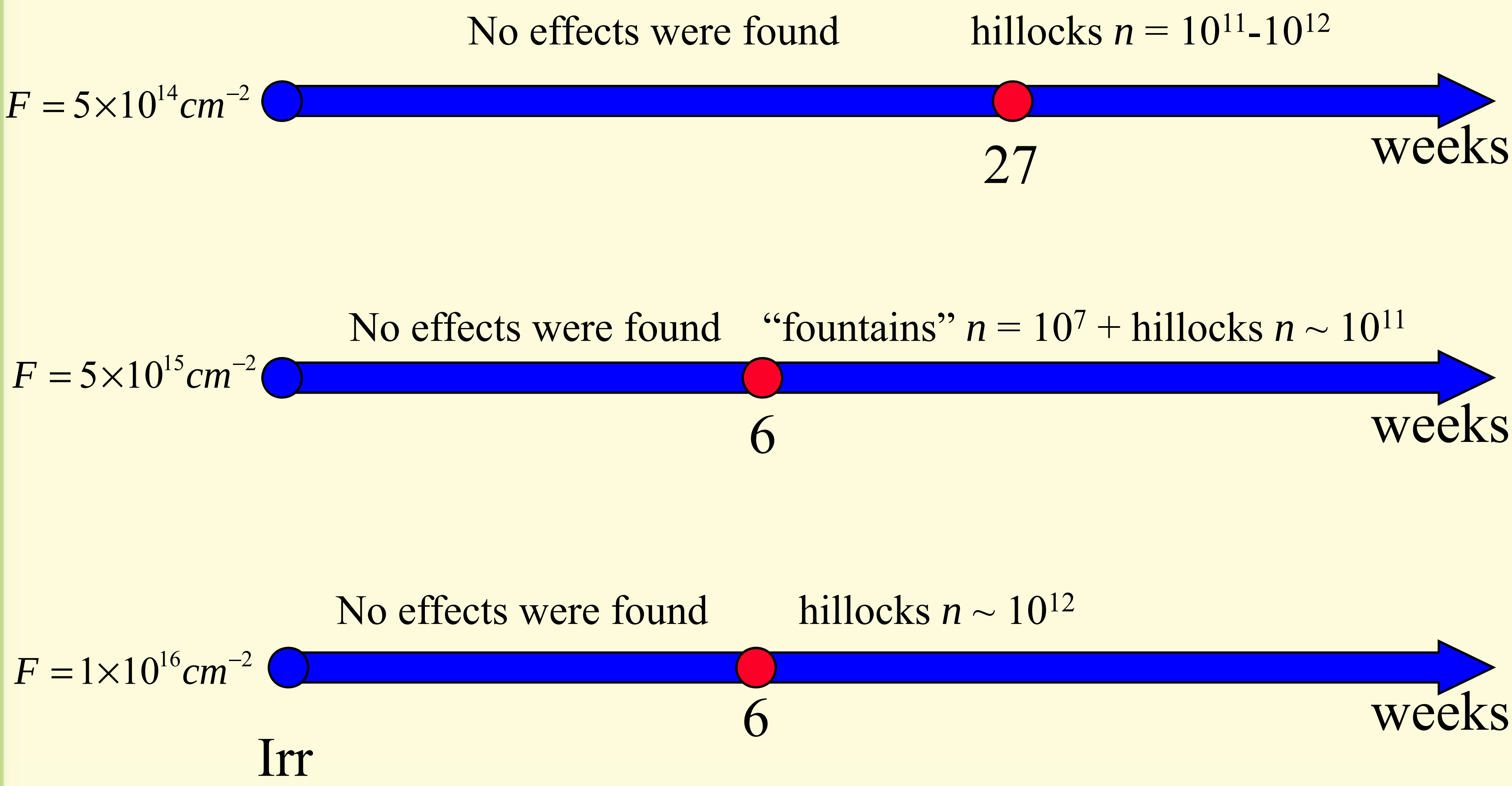
Proton irradiation

- Source parameters:
  - Ion H^+
  - Energy 21 MeV
- Fluences:
  - $5x10^{14}$ cm^{-2}
  - $5x10^{15}$ cm^{-2}
  - $1x10^{16}$ cm^{-2}
- Assembly parameters:
  - n-Si (100)
  - specimen thickness 0.3 mm
  - 12 plates in the assembly





AFM Investigation



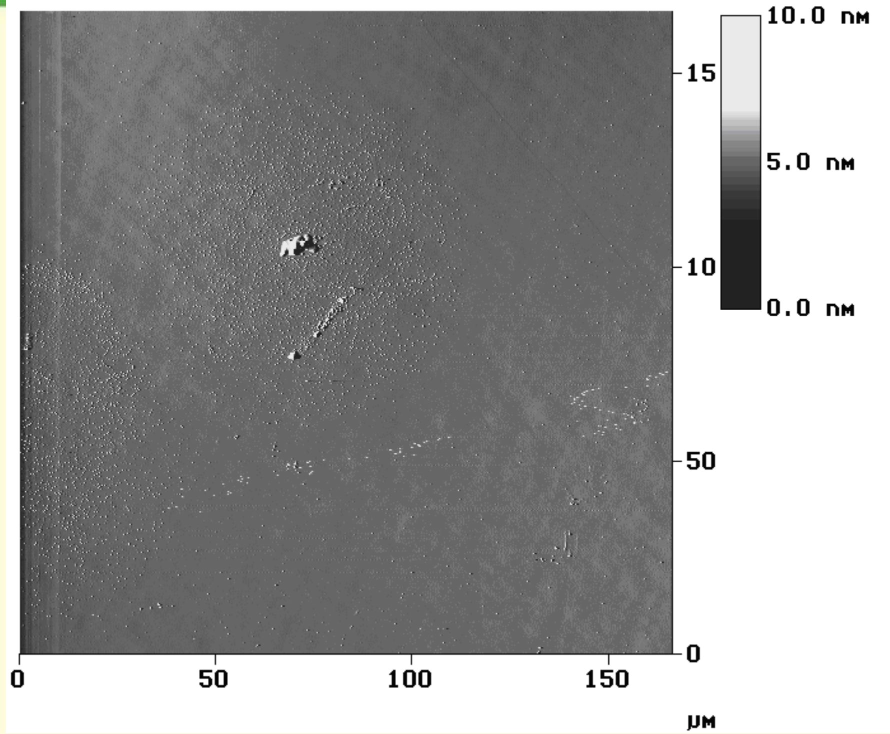
Inhomogeneous nucleation

•Round shaped areas filled with hillocks had emerged on the plates, irradiated up to $F=5x10^{15}$ cm^{-2}, after 5 weeks.

•Parameters of this “fountains”:

- d = 10 - 100 μm
- h = 5 - 10 nm
- $n = 10^7 - 10^8$ m^{-2}
- $n_h \sim 3x10^{10}$ m^{-2}

• the rest of the surface was covered with hillocks $n \sim 10^{10}$ m^{-2}.



Two types of “fountain” were found:

•with round areas with homogeneous distribution of hillocks (they are the biggest)

•with increasing hillock number density toward the center

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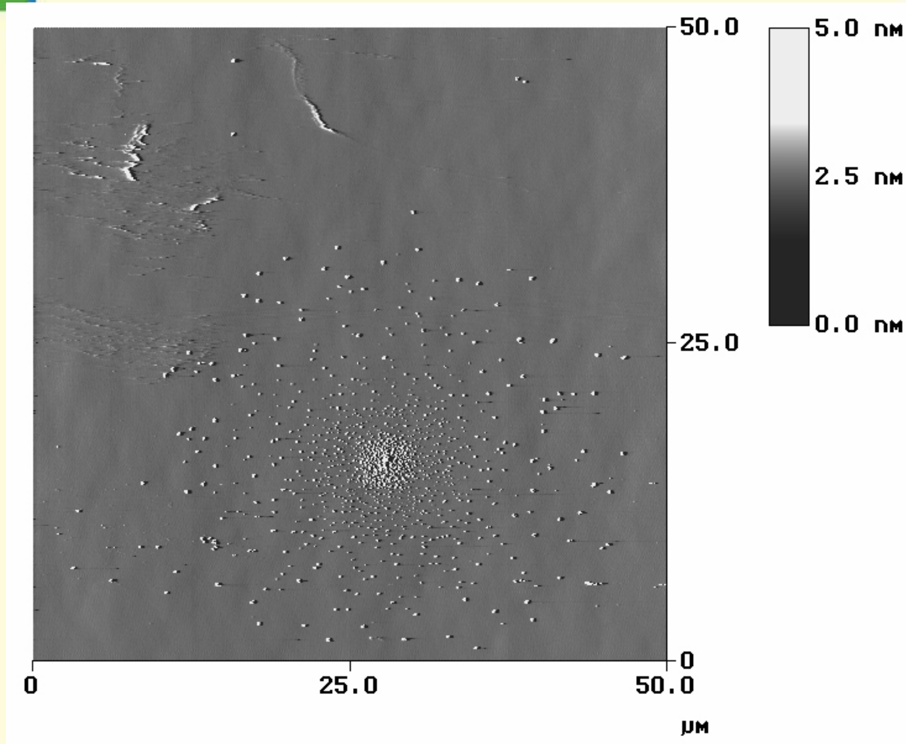

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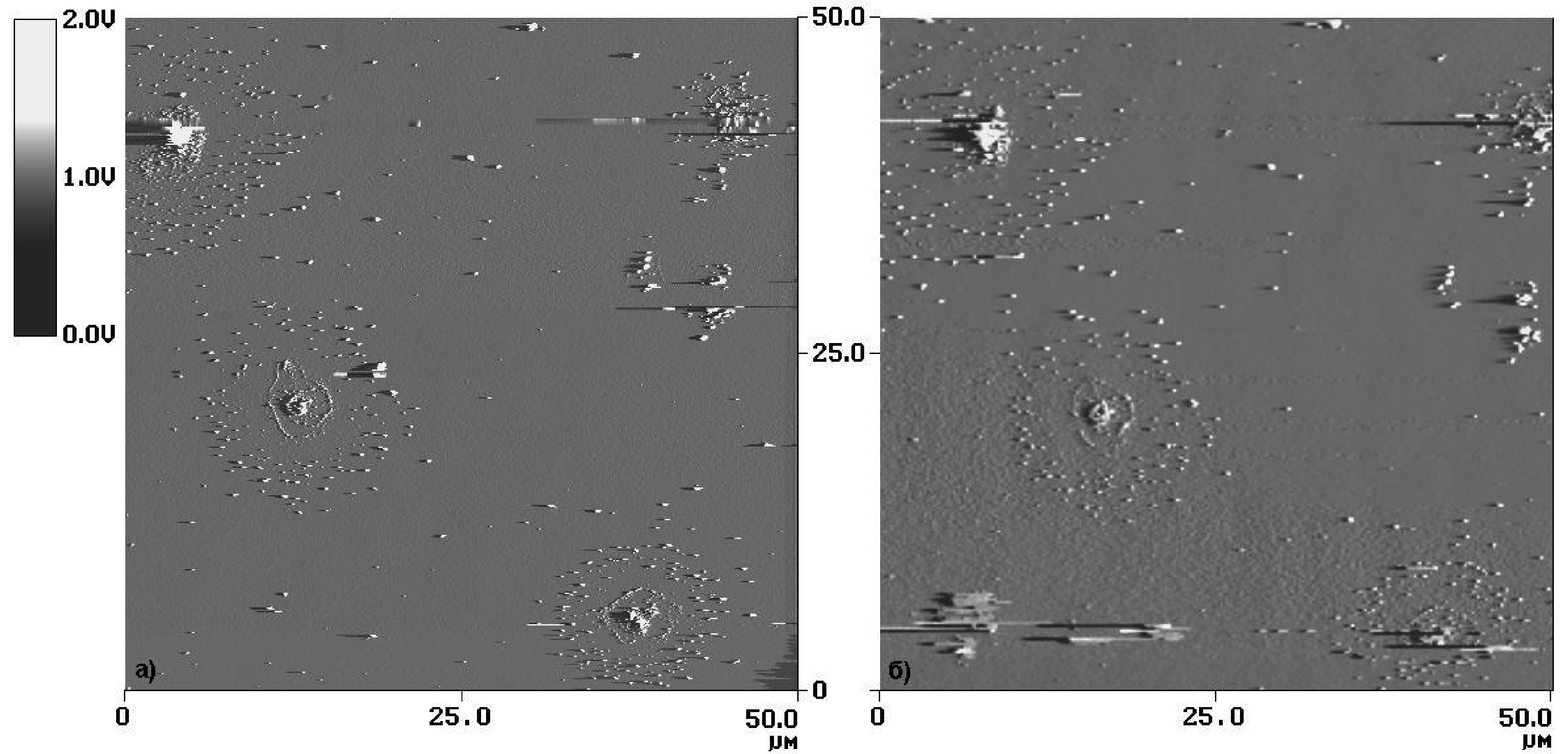
Annealing

protons, 21 MeV, F=5x10^{15} cm^{-2}

Preliminary annealing at T=100^{o} C, t=20 min Further annealing at T=300^{o} C, t=20 min



Annealing leads to "fountains" formation on earlier stages (accelerates nucleation)

Conclusions

- High energy ion irradiation results in surface modification (hillocks formation)
- These precipitates are considered to consist of silicon dioxide
- Hillocks nucleation reveals a considerable delay (weeks, months) which depends on dose.
- Hillocks formation is a thermal activated process. Heating is increasing this process rate.
- Presence of the considerable hillock nucleation delay indicates that "tracks" influence is minimal (if any) in this process.
- Inhomogeneous hillock nucleation on structural defects (dislocations, etc.) becomes possible at intermediate fluences. As result fountain-like structures emerge.

Discussion

- ✓ Hillocks nucleation processes: nucleation is considered to be connected with recombination of defects that have been created inside irradiated material (during irradiation).

- ✓ Limiting factors (hillocks nucleation and growth):
  room temperature irradiation: defects mobility
  $D_V \sim 10^{-8}$-10^{-9} cm^2/s, $D_I \sim 10^{-4}$ cm^2/s, etc.

- ✓ For binding of defects recombination and hillocks nucleation experiments with simultaneous (parallel) investigation of surface and volume defects concentration are required.