

12-4-2017

PRIMARY RADIATION DAMAGE IN METALS $\frac{1}{13}$

PART II

• "ION BEAM MIXING" BROADLY REFERS TO THE RELOCATION OF ATOMS IN ENERGETIC DISPLACEMENT CASCADES + HENCE REPRESENTS A BASIC COMPONENT IN DESCRIBING THE PRIMARY STATE OF DAMAGE.

→ IN PURE ELEMENTS MIXING HAS LITTLE CONSEQUENCE ~~FOR~~ FOR THE EVOLUTION OF THAT MATERIAL UNDER PROLONGED IRRADIATION.

→ MOST METALS OF INTEREST ARE COMPOSED OF 2 OR MORE PHASE ALLOYS IN METALS + COMPOUNDS IN SEMI CONDUCTORS + INSULATORS.

EXAMPLE: LOW-TEMP FAST γ IRRADIATION OF Cu_3Au
-1940s

INCREASE IN ELECTRICAL RESISTIVITY IS A RESULT OF MANY Cu + Au ATOMS EXCHANGING LOCATIONS FOR EVERY FRENKEL PAIR CREATED

- 3 MECHANISMS OF "ION BEAM MIXING" HAVE BEEN IDENTIFIED.

I. RECOIL IMPLANTATION

AS ENERGETIC IONS SLOW DOWN IN SOLID TARGETS THEY UNDERGO A SERIES OF COLLISIONS WITH TARGET ATOMS VIA SCREENED COULOMB INTERACTION.

TWO CONSEQUENCES OF COULOMB INTERACTION

1. → INITIAL ION ONLY SLOWLY CHANGES ITS INCIDENT DIRECTION.

2. → XFERES ENERGY TO ONLY A FEW ATOMS.

RESULTING IN A FEW TARGET ATOMS RECEIVING HIGH ENERGIES, WITH MOTION CLOSE TO THE DIRECTION OF INCIDENT ION.

- RECOIL IMPLANTATION CAN PLAY AN IMPORTANT ROLE, BECAUSE A FEW ATOMS CAN RECOIL LARGE DISTANCES, WHICH IN TURN CREATE FISSION GAS BUBBLES OR DAMAGE OXIDE DISPERSION STRENGTHENED STEEL ALLOYS

2. BALLISTIC MIXING

MOMENTUM OF DISPLACED ATOMS IN ENERGETIC DISPLACEMENT CASCADES IS NEARLY ISOTROPIC.

- BALLISTIC MIXING OPERATES SIMILARLY TO DIFFUSION PROCESSES.
- "BALLISTIC" IN THE SENSE THAT ALLOY COMPONENTS FLOW DOWN GRADIENTS IN THEIR CONCENTRATIONS DURING PROLONGED IRRADIATION, NOT GRADIENTS IN CHEMICAL POTENTIAL.
- ~~THE~~ CALCULATION OF BALLISTIC MIXING FROM DEPOSITED DAMAGE ENERGY DENSITY:

$$e_{BM} = \frac{\Gamma_0 \zeta_{21} \lambda_c^2}{3N_0 E_c}$$

WHERE

~~THE~~ Γ_0 IS DIMENSIONLESS CONSTANT 0.608

$$\zeta_{21} = \frac{4(m_1 m_2)}{(m_1 + m_2)^2}$$

E_c IS MINIMUM ENERGY FOR ATOMIC DISPLACEMENT

λ_c IS MEAN RANGE OF A RECOIL DISTANCE OF ENERGY E_c

N_0 NUMBER OF ATOMS PER UNIT VOLUME

TYPICAL VALUES FOR $E_{BM} \approx \frac{10 \text{ } \overset{5}{\text{Å}}}{e} \quad \frac{4}{13}$
 $\approx 50 \text{ } \overset{5}{\text{Å}}^2 / \text{DPA}$

EXAMPLES: SELF ION IRRADIATION, $E_e = 25 \text{ eV}$

	10 keV	100 keV
Si	197 $\text{Å}^2 / \text{DPA}$	372
Cu	8.7	13.5
Al	15.5	21

③ THERMAL SPIKE MIXING

ATOMIC "JUMPS" DURING THERMAL SPIKE PHASE

THIS IS SIMPLY CALCULATED: NUMBER OF "JUMPS":

$$\eta = \int d^3r \int A e^{-Q/kT(r,t)} dt$$

WHERE JUMP RATE PER UNIT VOLUME OF GIVEN MATERIAL IS:

$$R = A e^{-Q/kT}$$

Q = IS ACTIVATION ENERGY BARRIER FOR ATOMIC JUMPING.

REDUCE TO ENGINEERING FORMULA

$$\eta = \frac{0.02226 A \epsilon_0^{5/3}}{C^{2/3} K Q^{5/3}}$$

WHERE $\epsilon \equiv$ IS INITIAL ENERGY OF CASCADE

$C \equiv$ SPECIFIC HEAT

$K =$ IS THERMAL CONDUCTIVITY

$Q =$ ACTIVATION ENERGY FOR DIFFUSION.

CLUSTERING MIGRATION

→ LOW TEMP $< 100K$ IRRADIATION, DEFECTS ARE IMMUBLE

→ TECHNOLOGICAL MATERIALS ARE TYPICALLY IRRADIATED AT HIGH TEMPERATURES

FOUND THAT PREDICTED NRT DISPLACEMENTS WERE MUCH HIGHER THAN OBSERVED.

→ ANNEALING . -

HIGH FLUENCE EFFECTS.

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DISCUSSION SO FAR HAS ONLY CONSIDERED DAMAGE PRODUCTION MECHANISMS BY INDIVIDUAL CASCADES.

WHEN FLUENCE IS HIGH ENOUGH, DAMAGE FROM CASCADES WILL START OVERLAPPING - RESULTING IN SEVERAL NON-TRIVIAL EFFECTS.

WE ARE BY SEMI COND.

▷ WHEN A PURE METAL, Cu , IS IRRADIATED DAMAGE PRODUCTION EFFICIENCY DECREASES & ULTIMATELY SATURATES.

IN Cu THIS HAS BEEN FOUND TO BE $\sim 1\%$ DISPLACED ATOMS.

▷ HIGH FLUENCE DPA BECOMES DISCONNECTED FROM ACTUAL # OF DEFECTS.

DPA 10 OR 100, DEFECT CONCENTRATION REMAINS ~ 0.01 .

THIS IS EXPLAINED BY Cu STRONG TENDENCY TO RECRYSTALLIZE.

THIS DOES NOT MEAN THAT OTHER KINDS OF MATERIAL DAMAGE DOES NOT OCCUR.

- VACANCIES MAY AGGLOMERATE TO VOIDS, WHICH LEADS TO SWELLING, EVEN THOUGH MATERIAL BETWEEN VOIDS MAY REMAIN IN ALMOST PERFECT CRYSTALLINE STATE.

METAL ALLOYS

MULTICOMPONENT ALLOYS HAVE SEVERAL MORE DISPLACEMENT ASPECTS COMPARED TO PURE ELEMENTS. ~~MULTIPLE ELEMENTS~~

- MORE COMPLEX DEFECT PRODUCTION, ESP. NEAR THRESHOLD DISPLACEMENTS.
- CHEMICAL MIXING
- SOLID STATE CRYSTALLINE-AMORPHOUS PHASE TRANSITIONS
- RADIATION-MODIFIED SOLUTE SEGREGATION + PRECIPITATION.

MULTIPLE ELEMENTS, EACH WITH DIFFERENT DISPLACEMENT ENERGIES, CREATES NEW DEFECT SCENARIOS.

EFFECTS ARE MOST PRONOUNCED FOR LOW PRIMARY KNOCK-ON ATOMS (PKA) ENERGY EVENTS, WHICH LEAD TO

PREFERENTIAL DISPLACEMENT OF THE LOWER MASS ELEMENT.

CONCEPT.

RPA · REPLACEMENTS PER ATOM.

ION BEAM MIXING IS A QUANTITY THAT DIRECTLY DEPENDS ON ATOM REPLACEMENTS IN A COLLISION CASCADE.

IN DENSE METALS ^{MAJORITY OF} ATOM MIXING IS HOT SPIKES. HENCE # OF ATOMS THAT ARE DISPLACED FROM THEIR INITIAL LATTICE SITE IN A CASCADE + END UP IN ANOTHER SITE ^{IS A} REPLACED ATOM.

RPA EQUATION

$$\xi_{RPA}(E) = \frac{N_{\text{TRUE-NUMBER OF REPLACED ATOMS}}}{N_{\text{NRT-PREDICTION}}}$$

$$\epsilon_{RPA}(\epsilon) = \left(\frac{b_{RPA}^{C_{RPA}}}{(2\epsilon_d/0.8)^{C_{RPA}}} + 1 \right) \frac{\epsilon^{C_{RPA}}}{b_{RPA}^{C_{RPA}} + \epsilon^{C_{RPA}}}$$

HAS LIMIT FOR HIGH ϵ

$$\epsilon_{RPA}(2\epsilon_d/0.8) = 1$$

$$N_{\text{REPAIRED-ATOMS}}(\epsilon) = \begin{bmatrix} 0 & \epsilon < \epsilon_d \\ 1 & \epsilon_d < \epsilon < 2\epsilon_d/0.8 \\ \frac{0.8\epsilon^{C_{RPA}}}{2\epsilon_d} \epsilon_{RPA}(\epsilon) & 2\epsilon_d < \epsilon < \infty \\ & \frac{0.8}{0.8} \end{bmatrix}$$

SEMI CONDUCTORS

PRIMARY DAMAGE PRODUCTION IN SEMI-CONDUCTOR ~~MATERIAL~~ IS ATTRIBUTED TO THE OPEN CRYSTAL STRUCTURE + MUCH SLOWER RECRYSTALLIZATION, WHICH LEADS TO THE POSSIBILITY TO FORM AMORPHOUS POCKETS.

▷ DEFECTS ARE ALSO STABLE AT ROOM TEMP.

PROLONGED IRRADIATION AT LOW TEMPERATURES, SEMI CONDUCTORS WILL BECOME COMPLETELY AMORPHISED, UNLIKE METALS WHICH CAN NEVER BECOME AMORPHISED. DAMAGE SATURATION IN METALS DOES NOT EXIST IN SEMI CONDUCTORS.

↳ HOWEVER THERE IS A TEMPERATURE ^{200 → 300°C} ABOVE WHICH SEMICONDUCTORS DO NOT AMORPHISE AT ANY FLUENCE.

ANNILING MECHANISM IN SEMI CONDUCTORS IS DIFFERENT FROM METAL, BECAUSE OF DEFECT MIGRATION + THERMAL RECRYSTALLIZATION.

BUT REQUIRES ELEVATED TEMPERATURE + IS NOT ACTIVATED BY THERMAL SPIKES + OVERLAPPING CASCADES

SO THERE IS ~~NOT~~ NO
"ATHERMAL DAMAGE"

AMORPHOUS MATERIALS

A COMMON MISCONCEPTION IS THAT IF RADIATION
INDUCED DAMAGE TURNS CRYSTALLINE MATERIAL
INTO AMORPHOUS MATERIAL, THEN AMORPHOUS MATERIAL
~~IS~~ CAN NOT BE DAMAGED

▷ WE'VE SEEN EVIDENCE PROVING THAT WRONG.
SUCH AS OUR IRRADIATION OF THE ~~TOTAL~~ SILICA-
BASED GLASS + ITS COLOR CENTERS CORRESPONDING
TO DANGLING BONDS OR IMPURITY DEFECTS.

HOWEVER

SINCE IT MAKES NO SENSE TO DISCUSS D.P.A.
IN AMORPHOUS MATERIALS, IT IS BETTER TO DESCRIBE
DAMAGE IN AMORPHOUS MATERIALS WITH
ENERGY DEPOSITED;

i.e. ~~is~~ Gy [J/kg]

PRELUDE TO A REVIEW

12/13

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- RADIATION FUNDAMENTALS, DEBRAY NEUMERLOGY, etc
- ALPHA PARTICLES: GENERATION, STOPPING POWER, KINEMATICS
- BETA DECAY: SOURCES, COMPLEX INTERACTIONS WITH MATTER
STOPPING POWER, L-FIG, RANGE
- Neutrons & fission
- GAMMA RAYS: γ -INTERACTION WITH MATTER
3-WAYS ...

APPLIED RADIATION INTERACTION WITH MATTER:
②
MEASURING IT.

- DETECTING RADIATION:
COMMON DETECTOR FUNDAMENTALS, GEOMETRY, EFFICIENCY, READ TIME
THEN DETECTING REGION:
- LOW, PROPORTIONAL, GEIGER
SCINT. + SEMI CONDUCTOR + SPECTROSCOPY
COMPTON SUPPRESSION
- DOSIMETRY + TERMS SUCH AS DOSE, EXPOSURE, $\frac{dE}{dx}$
BIOLOGICAL DOSIMETRY LET + ~~AND~~ BRAGG-GRAY PRINCIPLE
CHEMICAL DOSIMETRY
T.L.D.
- RADIATION EFFECTS ON MATTER: RADIATION ON WATER
(BIOLOGICAL SURROGATE FOR HUMANS)
MECHANISMS FOR DAMAGE IN INORGANIC, ORGANIC,
POLYMER & CHEMISTINE MATERIALS.
RADIATION INDUCED CHEMICAL YIELD

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- BIOLOGICAL EFFECTS: PHYSICAL, PRE-CHEM, CHEM, BIOLOGICAL

DOSE-RESPONSE RELATIONSHIPS, REC. BIO. EFF. R_D

- INDUSTRIAL STERILIZATION w/ γ -RAYS:

LETHALITY, DECIMAL REDUCTION RATE, STERILIZATION ASSURANCE LEVEL

- CONCEPTS OF RADIATION DAMAGE IN METALS (DPA, RPA)

TWO GUEST LECTURES.

ALICE MIGNERY \rightarrow NUCLEAR FORENSICS

LYNN EARLY \rightarrow RADIATION HARD SOLDIERS