MOVING INTRINSIC LOCALIZED MODES IN GERMANIUM PRODUCED BY A LOW ENERGY PLASMA

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Outline

We believe that there are moving intrinsic localized modes (ILMs) in germanium

- The defect E center
- The plasma source
- The annealing of defects with a plasma
- Comparison with phonons
- Characteristics of ILMs in Ge that we can estimate



Defects in germanium

- Can be produced by irradiation as 5 Mev alpha particles
- Some are unconvenient but some are of technological interest



The defects E center in germanium

- E center : vacancy bound to a substitutional Sb
- E center is an electron trap



Plasma source COPRA DN-160

- Inductively coupled (ICP)
- It can have low flux and low energy
- Ions impact almost perpendicular to the wafer



•Our experiment:

High pressure: p=0.1 mb

Very low flux: $\Phi=5.6 \times 10^{10} \text{ cm}^{-2} \text{s}^{-1}$

Low ion energy K=4 eV

Deep level transient spectroscopy (DLTS): Example



Defect A:

$$RW_1 = 80s^{-1} = e_n(T_A)$$
Defect B:

$$RW_1 = 80s^{-1} = e_n(T_B)$$

Defect C

Our basic experiment: 4 eV ICP plasma annealing



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1.-Sb doped Ge is damage with5 MeV alpha particles

2.- Rest 24 hours

3.-Au diode is evaporated in half the sample (half A)

4.- DLST in A (black, alphas only)5.-ICP in A and B

6.- Au diode in B

7.- DLTS in A (red-dashed) (red, ICP on Au)

8.- DLTS in B (blue, ICP on Ge) 8

Our basic experiment: Facts

- 1.-Sb concentration: 1.3×10^{15} cm⁻³ (n_i= 2.4×10^{13} cm⁻³) ; 1 Sb per 10⁸ Ge
- 2.- Metal (Au) thickness: 25nm
- 3.- After ICP on Ge the E center concentration drops 29% from $N_T = 1.07 \times 10^{14}$ cm⁻³
- 4.- If ICP is done on Au, the E center reduction is smaller, but exists.
- 5.- ICP is done for 30 minutes in 10 minutes intervals to prevent heating
- 6.- Defect annealing occurs up to 2.600 microns or 4600 lattice units
- 7.- If the plasma ion energy is increased the effect is smaller
- 8.- Thermal annealing has to be done at 157 C to obtain a similar effect

Our hypothesis: Ar ions impacting on Ge produce ILMs, which travel through Ge and anneal the defects. Why?

1.-ILMs with MD in metals by Hyzhnyakov group have 0.5-5 eV

2.-The maximum energy transfer from Ar to Ge is 3.6 eV

3.- The energy for annealing an E center is about 1.0 eV.

4- Therefore, the energy delivered by Ar atoms has to remain localized while traveling 10⁴ lattice units

5.- Increasing the energy of the plasma does not enhance the effect, this is typical of ILM which often have a definite range or energies.

6.- At least stationary ILMs have obtained for Si and Ge with MD.

Some estimate numbers for ILMs

1.-Ion current can be measured, $\Phi_{Ar} = 5.6 \times 10^{10} \text{ cm}^{-2} \text{s}^{-1} \approx 0.01 \text{ ions}$ per squared lattice unit and minute

2.- ILM creation efficiency: γ : $\Phi_{\text{ILM}} = \gamma \Phi_{\text{Ar}}$; $\gamma < 1$

3.-Energy and velocity of ILMs $E_{\text{ILM}} \approx 3 \,\text{eV}; \quad c_s = 5400 \,\text{m/s}$

3.-Density of of IlMs: $n_{\rm ILM} = \frac{4}{3}$

$$c_{\rm ILM} = \frac{\Phi_{\rm ILM}}{c_s} \approx \gamma \times 2.3 \times 10^7 \, {\rm cm}^{-1}$$

4.- Energy density for ILMs $\rho_{ILM} = n_{ILM} E_{ILM} \approx \gamma \times 3 \times 10^5 \text{ eV/cm}^3$

Some estimate numbers for phonons at annealing temperature 157 C



1.-Phonon energy, Einstein model $E_{\rm Ph} \approx 8.5 \, {\rm Thz} \approx 0.035 {\rm eV}$ 2.-Number of phonons at annealing temperature $T_{\rm A} = 157 \, {\rm C}$ $n_{\rm Ph} = \frac{3n_{\rm Ge}}{\exp(E_{\rm Ph}/k_{\rm P}T_{\rm A}) - 1}$ 3.-Phonon energy density at T_A $\rho_{\rm Ph} = n_{\rm Ph} E_{\rm Ph}$ 4.- Ratio of energy densities for the same

annealing rate

$$\frac{\rho_{\rm Ph}}{\rho_{\rm ILM}} \approx 10^{-16}$$

ILM-defect interaction cross-section and ILM creation efficiency

Minimal interacion cross-section $\sigma_0 = n_{Ge}^{-2/2}$

$$\sigma_0 = n_{\rm Ge}^{-2/3} \approx 10^{-15} {\rm cm}^2$$

ILM-defect interaction cross-section $\sigma_{\text{ILM}} = \alpha \sigma_0$; $\alpha > 1$

$$\frac{1}{N_T}\frac{dN_T}{dt} = \boldsymbol{\sigma}_{\mathrm{ILM}}\boldsymbol{\Phi}_{\mathrm{ILM}} = \boldsymbol{\alpha}\,\boldsymbol{\gamma}\,\boldsymbol{\sigma}_0\boldsymbol{\Phi}_{\mathrm{Ar}}$$

 $\alpha \gamma = (\text{ILM creation efficiency}) X (relative cross section)~ 3.6$

$$\alpha \approx 6^2 \sigma_0 \quad ; \quad \gamma \approx \frac{1}{10}$$

Conclusions:

1.- Plasma ions of 4eV produces annealing of defects very deep in Ge

Likely conclusions:

- 2.- 4 eV Ar hits produce ILMs in Ge with very high efficiency
- 3.- ILMs of energy ~3eV travel distances of the order of at least 10⁴ lattice units or 2.6 microns
- 4.- The annealing efficiency of ILMs with respect to phonons is extremely large
- 5.- Ar hits are very efficient at producing ILMs in Ge

References

- 1. J. F. R. Archilla, S. M. M. Coelho, F. D. Auret, V. I. Dubinko and V. Hizhnyakov Experimental observation of moving intrinsic localized modes in Germanium Submitted (2013), arXiv:1311.4269
- V. Hizhnyakov, M. Haas, A. Shelkan, and M. Klopov. Theory and MD simulations of intrinsic localized modes and defect formation in solids. Physica Scripta (2014) to appear, arXiv:1311.4325.
- 3. S. M. M. Coelho and F. D. Auret and P. J. Janse van Rensburg. Unexpected properties of the inductively coupled plasma induced defect in germanium. Physica B (2013), in press, available on line.
- 4. M. Haas, V. Hizhnyakov, A. Shelkan, M. Klopov, and A. J. Sievers. Prediction of high-frequency intrinsic localised modes in Ni and Nb Phys. Rev. B 84 (2011) 144303.
- 5. V. I. Dubinko, P. A. Selyshchev and J. F. R. Archilla. Reaction-rate theory with account of the crystal anharmonicity. Phys. Rev. E, 83 (2011) 041124.

Ion energies

• At p ~ 0.1mb, the plasma sheath is collisional, so ion energy is controlled by pressure

• Mean free path inversely proportional to n_{Ar} and p



Ion flux

• We couldn't measure the current for p > 0.06 mb



Very low flux:

 $\Phi = 5.6 \times 10^{10} \text{ cm}^{-2} \text{ s}^{-1}$