Analysis of metal induced recombination losses between phosphorus emitter and silver contacts and its correlation with c-Si solar cells efficiency

M.S. Jeong[1,2], S. J. Choi[1,3], K.H. Min[1,2], M. G. Kang[2], J. I. Lee[2], S. E. Park[2], D. H. Kim[1] and H. E. Song[2,*]

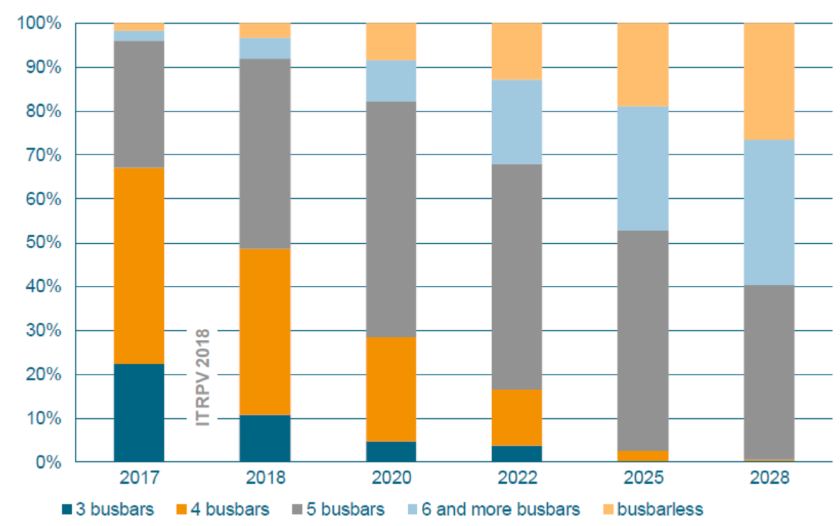
[1] Department Materials Science and Engineering, Korea University, Seoul, Korea

[2] Photovoltaic Laboratory, Korea Institute of Energy Research, Daejeon, Korea

[3] Department of energy and Environment, Graduate School of Energy and Environment(Green School), Korea University, Seoul, Korea

Introduction

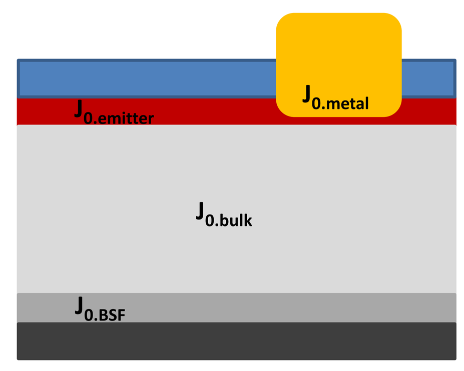
▪ Why metal contact recombination is important?



ITRPV 9th edition 2018 report

- As the contact area of the metal electrode increases, the surface recombination velocity increases
- Increased surface recombination velocity limits open-circuit voltage(V_{oc}) in crystalline silicon solar cells
- The surface recombination velocity can be represented by saturation current density(J_0)

▪ Saturation current density (J_0)

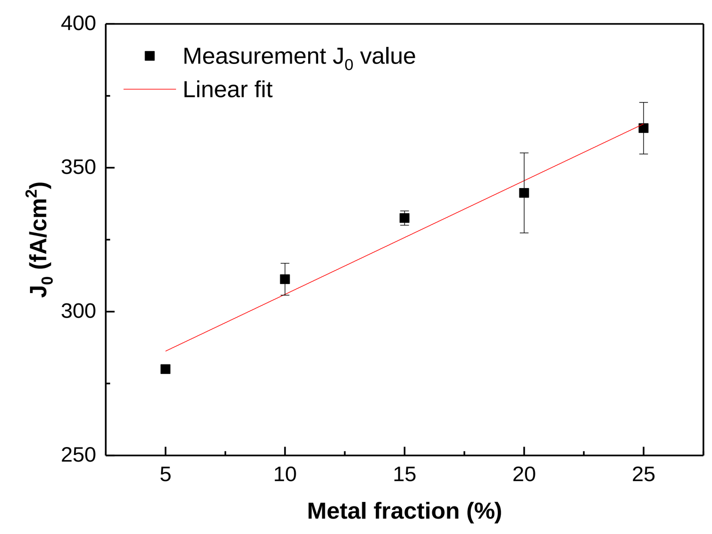


Total J_0 is the sum of all J_0 component

$J_0 = J_{0.bulk} + J_{0.BSF} + J_{0.metal}\,(f_m) + J_{0.pass}\,(1\text{-}f_m)$

- $J_{0.emitter}$ is the sum of $J_{0.pass}$ and $J_{0.metal}$
- $J_{0.pass}$ is the emitter saturation current density values where the emitter is passivated with SiN_x
- $J_{0.metal}$ is the emitter saturation current density in emitter-metal interface
- Emitter damage caused by the Ag crystallites during the high-temperature firing step
- Ag paste fires through the passivation layer to contact the emitter
  → Ag crystallites grow into Si and increase the $J_{0.metal}$

▪ $J_{0,metal}$ calculation method



- $J_{0.metal}$ was extracted by the relationship between metal fraction and J_0

$J_0 = J_{0.bulk} + J_{0.BSF} + J_{0.metal}\,(f_m) + J_{0.pass}\,(1\text{-}f_m)$

Slope $= J_{0.metal} - J_{0.pass}$

$\therefore\ J_{0.metal} = \text{Slope} + J_{0.pass}$

Experimental

- Texture (Wafer spec : P-type, ρ = 1 - 3 Ω·cm, thickness = 170μm)
- $POCl_3$ doping (Sample A = 8.82E20 atom/cm³, Sample B = 6.24E20 atom/cm³, Reference = 2.11E20 atom/cm³)
- PSG removal (HF 10%, 30s)
- Anti-reflection coating (SiN_x 80nm, double side)
- Screen printing (single side, Ag paste, metal fraction = 0 - 25%, size = 4 X 4cm²)
- Firing (belt furnace, beak temperature = 875, 925 and 975℃)
- Laser cutting (size = 4 X 4cm²)
- Metal removal (HNO_3 68%, 15min)
- Measurements (using QSSPC, SEM, SIMS, TEM, TLM, ICP-OES)

Results & Discussion

➢ Emitter property and saturation current density

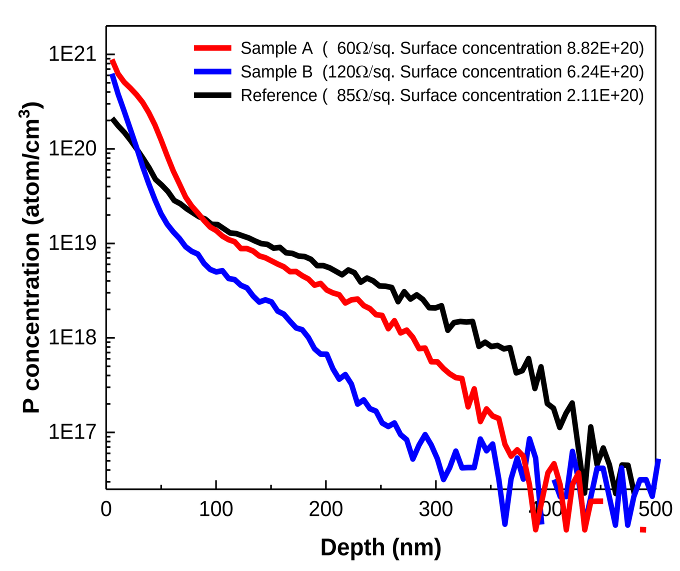


Fig 1. SIMS profile with various surface phosphorous doping concentration

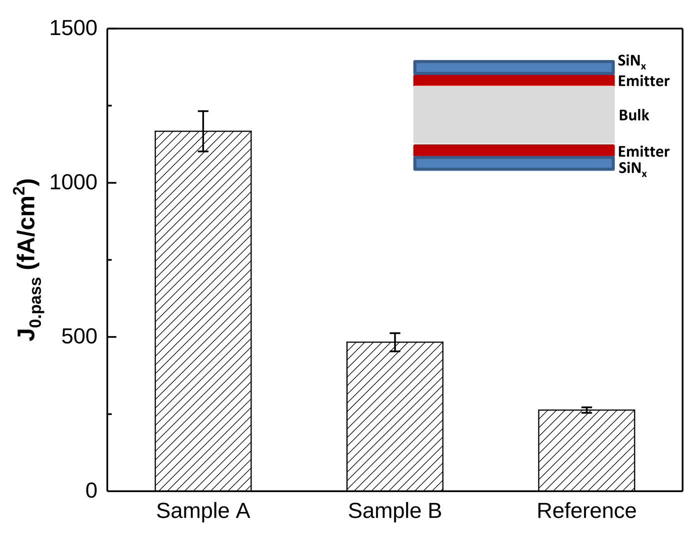


Fig 2. The emitter saturation current density values ($J_{0.pass}$) of the SiN_x passivated silicon, measured by QSSPC

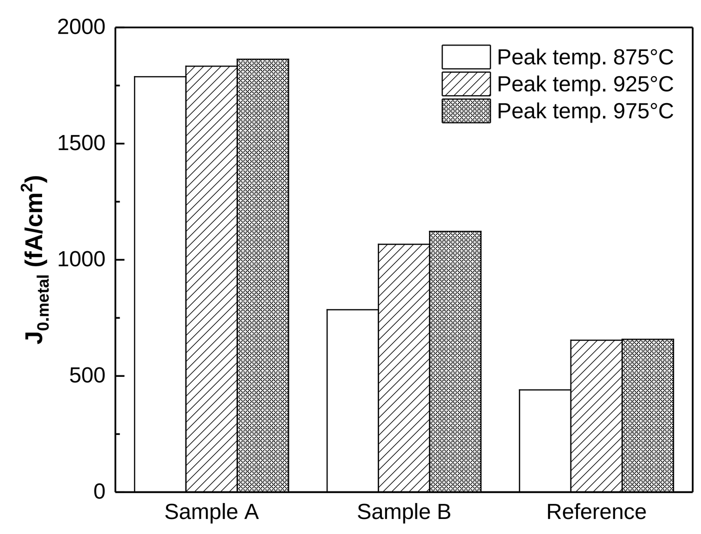
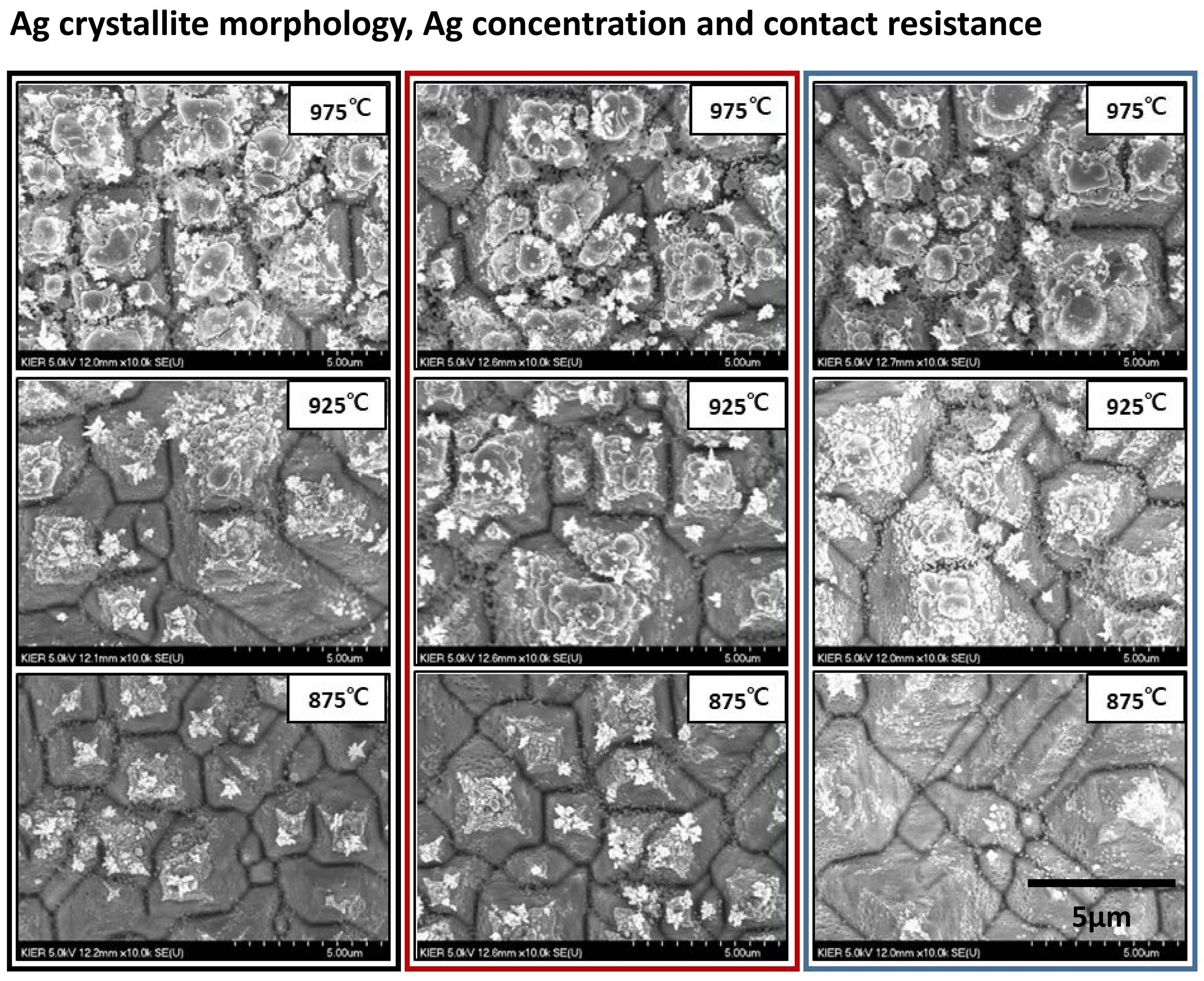


Fig 3. The emitter saturation current density values of the metal contact ($J_{0.metal}$) with various surface doping concentrations and firing peak temperatures

- Surface phosphorous concentration
  → Sample A (8.82E+20 atom/cm³)
  → Sample B (6.24E+20 atom/cm³)
  → Reference (2.11E+20 atom/cm³)
- As surface doping concentrations decrease
  → Emitter saturation current ($J_{0.pass}$) decreases
  → $J_{0.pass}$ depends on surface doping concentration
- As firing peak temperatures increase
  → $J_{0.metal}$ increases
- The increase of the $J_{0.pass}$ and $J_{0.metal}$ reduces V_{oc} and increases the surface recombination velocity

➢ Ag crystallite morphology, Ag concentration and contact resistance



Sample A **Sample B** **Reference**

Fig 4. SEM image of silicon surfaces after removal of the bulk of the Ag metal and the glass frits with various surface doping concentration and firing peak temperatures

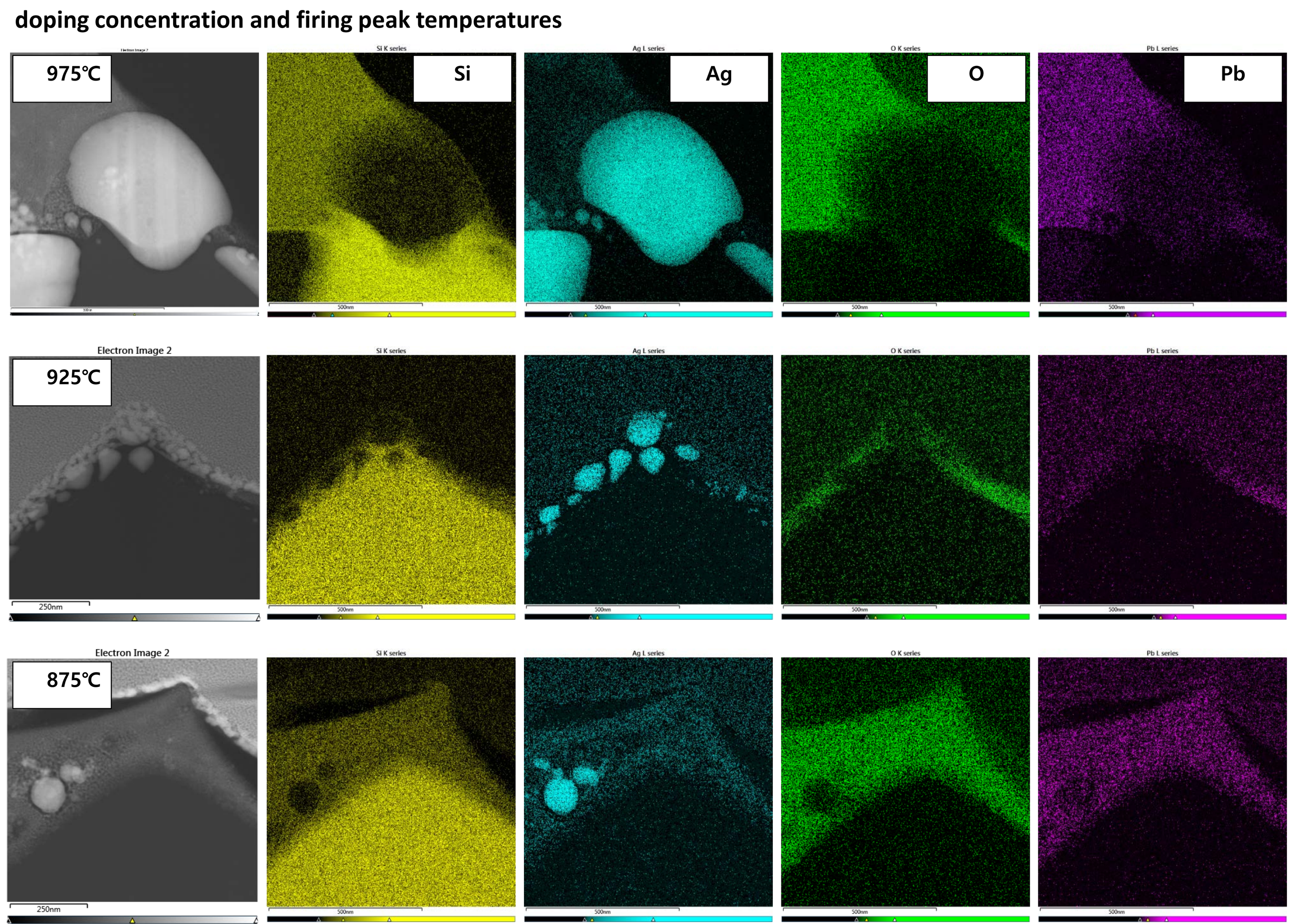


Fig 5. TEM-EDS mapping images at the interface of the silicon and metal contact

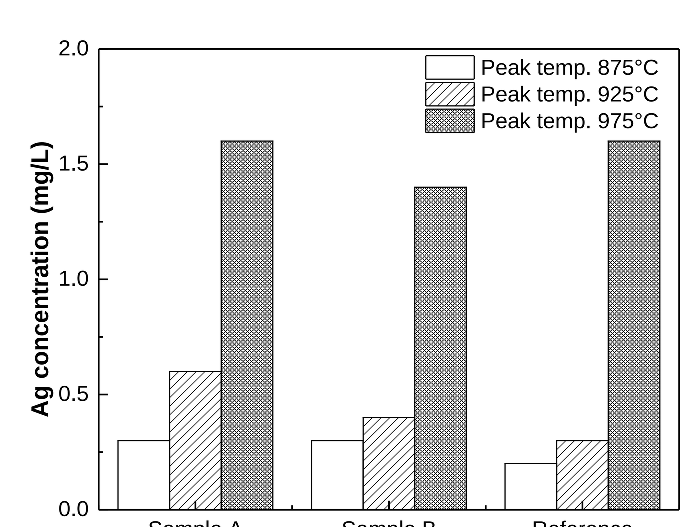


Fig 6. ICP-OES measurements of Ag crystallites with various surface doping concentrations and firing peak temperatures

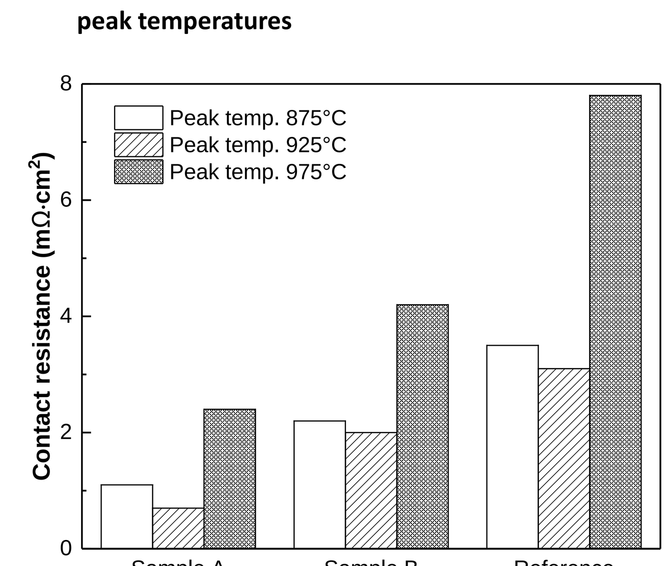


Fig 7. The contact resistance values by TLM measurements in the dependence of surface doping concentrations and firing peak temperatures

- As firing peak temperatures increase
  → Faster diffusion velocity of fluidized glass frit and Ag ions
  → Ag crystallites size and distribution increased
  → More etched emitter surface
  → Increasing contact area between silicon and Ag crystallite
  * $2Ag_2O_{(in\ glass)} + Si_{(s)} \rightarrow 4Ag_{(s)} + SiO_{2(in\ glass)}$
  * High $J_{0.metal}$, high contact resistance

➢ V_{oc} calculation and surface recombination velocity

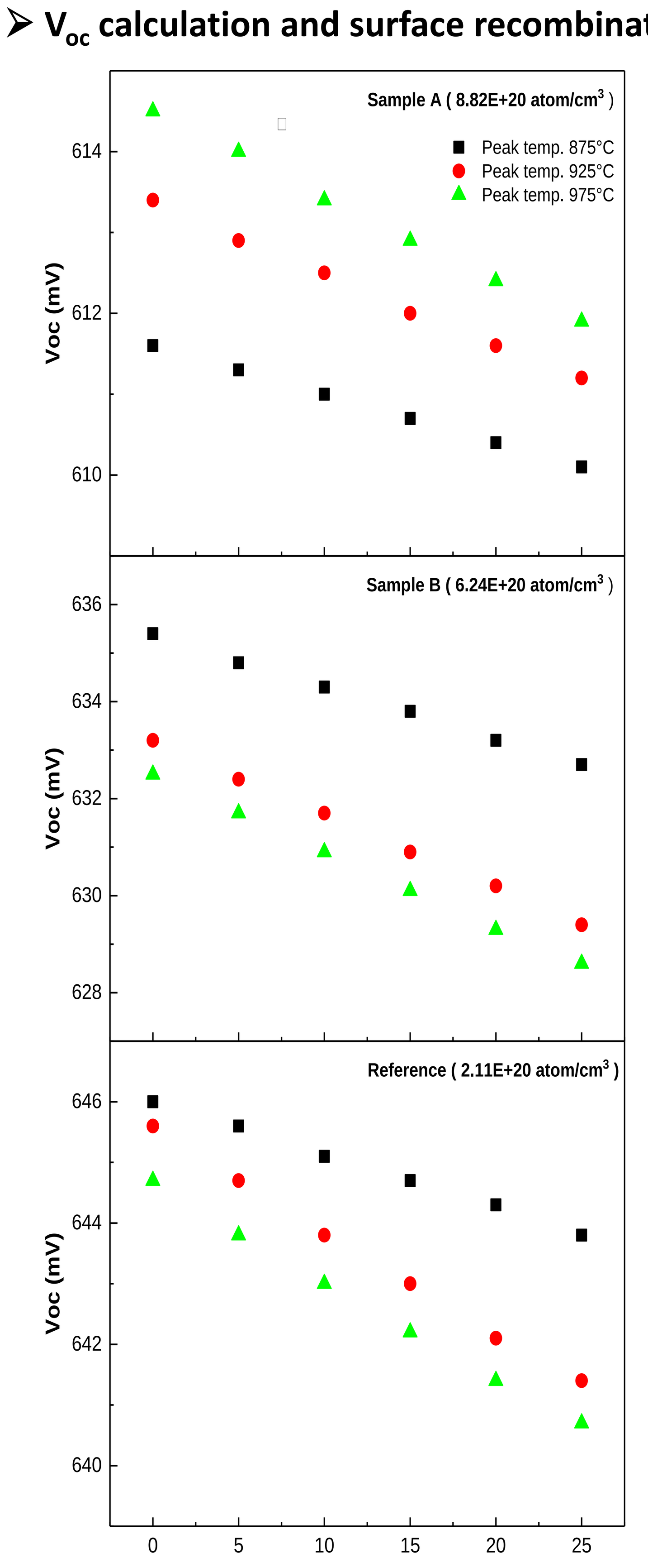


Fig 8. The V_{oc} values as a function of the metal fraction with various surface doping concentration and firing peak temperature

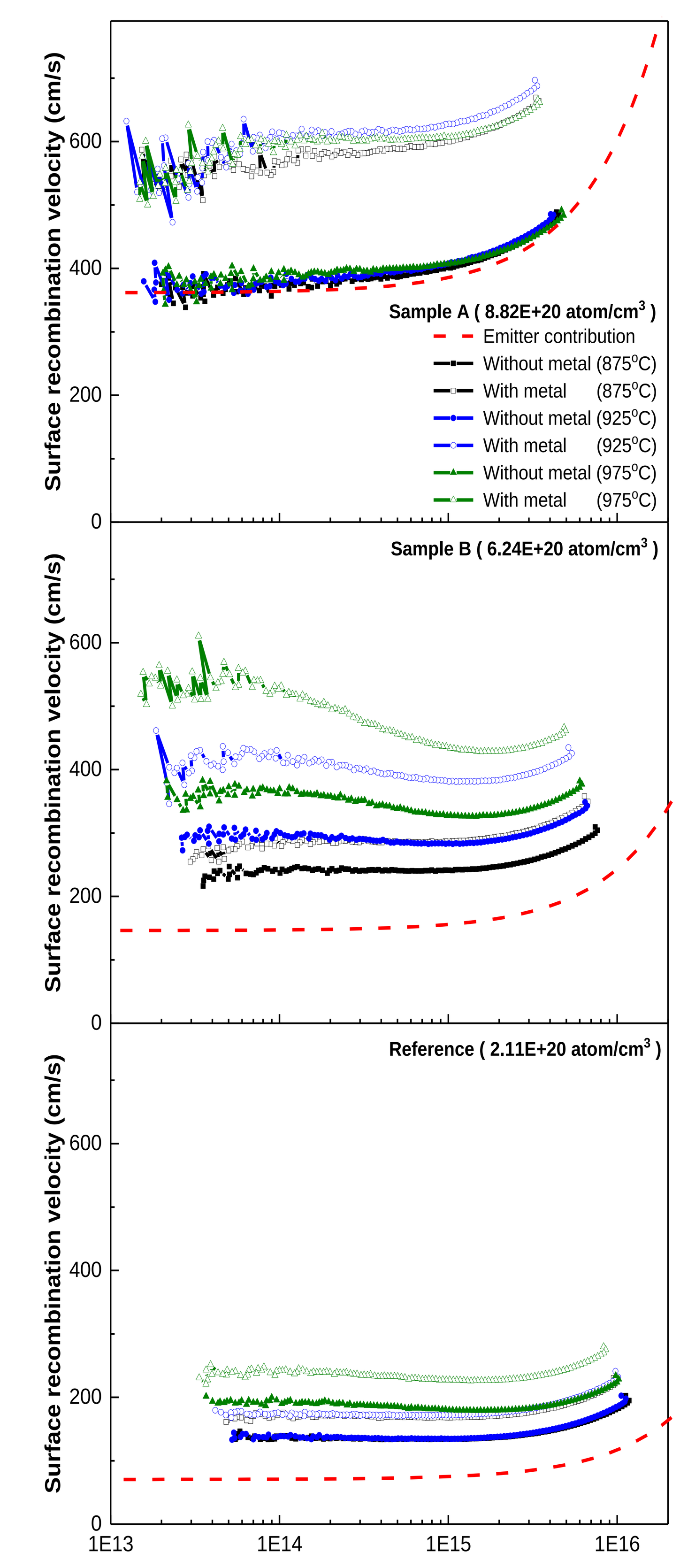


Fig 9. The surface recombination velocity values obtained by QSSPC measurements of samples with and without metal electrode, depending on surface doping concentration and firing peak temperature

- As the surface doping concentration decreases, the initial V_{oc} increases
  → because $J_{0.pass}$ is low
- Increase of metal fraction indicates increase of $J_{0.metal}$
- As the $J_{0.metal}$ increases, the V_{oc} decreases
- Surface doping concentration decreases, the surface recombination velocity decreases
- When the metal electrode is present, the recombination velocity increases

$$J_{o.emitter} = \frac{S_{eff}}{qn_i^2} \times (N_A + \Delta n)$$

- Surface recombination velocity and $J_{0,emitter}$ are proportional, they affect the decrease in V_{oc}

Conclusion & Future work

- Using QSSPC measurements, $J_{0,metal}$ values were analyzed according to the metal fraction
- The firing peak temperature and surface concentration affect metal-Si interface and $J_{0,metal}$ values
- The difference in Ag crystallite formation was revealed in various firing temperatures
- The optimization of $J_{0,metal}$ is significant to improve the efficiency of the c-Si solar cells

❖ Future work

- Prediction of metal penetration depth between metal-silicon interface
- Analysis of morphology between metal electrode and silicon interface
- Front electrode optimization considering $J_{0,metal}$

Metallization & Interconnection Workshop 2019
8th Workshop on Metallization & Interconnection for Crystalline Silicon Solar Cells

KOREA UNIVERSITY
KIER 한국에너지기술연구원 KOREA INSTITUTE OF ENERGY RESEARCH