**Introduction**

Why metal contact recombination is important?

- 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 ($J_0$)**

- $J_0$ is the sum of all $J_0$ component: $J_0 = J_{0,BSF} + J_{0,metal} + J_{0,emitter}$.
- $J_{0,BSF}$ is the emitter saturation current density values where the emitter is passivated with $SiO_x$.
- $J_{0,metal}$ is the emitter saturation current density in emitter-metal interface.
- Emitter damage caused by the Ag crystallites during the high-temperature firing step.
- As firing peak temperatures increase, more Ag pastes fires through the passivation layer to contact the emitter.
- $J_{0,emitter}$ is the sum of $J_{0,pass}$ and $J_{0,metal}$.

**Calculation method**

$$J_0 = J_{0,BSF} + J_{0,metal} + J_{0,emitter}$$

**Results & Discussion**

**Emitter property and saturation current density**

- Surface phosphorus concentration
  - Sample A: $8.82 \times 10^{20}$ atom/cm$^3$
  - Sample B: $6.24 \times 10^{20}$ atom/cm$^3$
  - Reference: $2.11 \times 10^{20}$ atom/cm$^3$

**Ag crystallite morphology, Ag concentration and contact resistance**

- As surface doping concentration decreases, $J_{0,emitter}$ decreases.
- Emitter saturation current concentration decreases because $J_{0,emitter}$ depends on surface doping concentration.
- The increase of $J_{0,pass}$ and $J_{0,metal}$ reduces $V_{oc}$ and increases the surface recombination velocity.

**Experimental**

**$V_{oc}$ calculation and surface recombination velocity**

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

**Conclusion & Future work**

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

- Using QSSPC measurements, $J_{0,emitter}$ values were analyzed according to the metal fraction.
- The firing 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 $J_{0,emitter}$ is significant to improve the efficiency of the c-Si solar cells.