Green laser annealing with metal absorber

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1. Introduction
Ultra-shallow low-resistive junction formation is a key technology for MOSFET scaling. Micro- to nanoseconds short-duration annealing is currently being developed for sub 20 nm junction formation [1-4]. We have obtained a sheet resistance of 460 Ω/sq. for the junction depth of about 20 nm using KrF excimer Laser Annealing (LA) [2]. However, high-power excimer laser has a problem concerning equipment size and maintenance. In this paper, LA with 532 nm all-solid-state green laser is described. Because of deep penetration depth in Si, about 1.532 μm, most part of laser energy is consumed for meaningless heating (Fig. 1). As a result, EL (laser energy density) necessary for the dopant activation becomes larger. We introduced a light absorber that has small penetration depth to solve this problem [5]. The absorber reduced EL necessary for dopant activation. Utilizing one-dimensional thermal diffusion analysis, part of experimental results were explained [6].

2. Sample preparation and simulation model
TiN and Mo were chosen as candidates of the absorber. Since they form silicide reacting with Si by high temperature processing, direct deposition of these materials on a Si substrate should be avoided. Sample structure is illustrated in Fig. 2. A 2 nm oxide layer was formed on a silicon substrate before depositing the absorber. The oxide was used for screen oxide and reaction barrier. Then, Sb⁺ was implanted. A surface of some specimens were pre-amorphized with Ge⁺ prior to the Sb⁺ implantation. After the ion implantation, TiN or Mo was deposited on the screen oxide as the light absorber. The pulse width of all-solid-state green laser was 120 ns.

Thermal diffusion during LA was analyzed with a simple one-dimensional thermal diffusion model. Thermal diffusion and generated heat by the laser absorption was formulated assuming heat insulation at the surface and constant temperature at the bottom. Thermal conductivity for each material was treated as a function of temperature. Reflectivity for Si was inherent in each Si phase. The phase transition between solid-Si and liq-Si was expressed with an enthalpy-based method.

3. TiN and Mo absorber
Figure 3 shows relationships between sheet resistance and EL for the various specimens. Sheet resistance reduction from several kΩ/sq. to about 1 kΩ/sq. is mainly explained by a-Si melting by laser heating, as discussed in our previous reports [2, 7]. By the introduction of TiN absorber, EL necessary to make the sheet resistance be lower than 1 kΩ/sq. was decreased by about 0.3 J/cm², as expected. On the other hand, Mo absorber oppositely increased the EL by 0.4 J/cm².

One-dimensional thermal diffusion was analyzed to explain these results. Figure 4 shows the calculated relationship between melt depth and EL. Reduction in melting threshold EL by TiN absorber was qualitatively explained. However, increase in the EL by Mo absorber was not. Large difference in thermal conductivity should be noted. Thermal Conductivities for Mo and TiN are 85 Wcm⁻¹K⁻¹ and 8.4 Wcm⁻¹K⁻¹ at about 1300°C. High thermal conductivity of the absorber gives rise to not negligible thermal diffusion to outside of the irradiation area. Two-dimensional simulation that can treat lateral thermal flow is necessary to clearly discuss this problem.

Figure 5 shows variation in Sb depth profiles due to EL increase. In the case of no absorber, in spite of large EL difference, obtained junction depth was almost constant. On the other hand, for the specimen with the TiN absorber, EL increase by only 0.2 J/cm² lead to severe junction spreading indicating melting of both a-Si and underneath c-Si layers. Therefore, process window to form shallow junction is very narrow for the TiN absorber. This difference is attributed to the absence of a negative feedback effect by reflectivity reduction due to surface melting. In the case of annealing without the absorber, surface melting decreases effective laser energy density for the latter half of laser pulse duration because of high liq-Si reflectivity. Since a metal absorber does not show such a change in reflectivity, most part of irradiated light was absorbed. Thus, over-melt to c-Si was brought about for the specimen with the TiN absorber.

4. Summary
Green laser annealing with the light absorber has been investigated. By adding a TiN absorber layer, sheet resistance lower than 1 kΩ/sq. was obtained for the lower EL. Though this result was explained with one-dimensional thermal diffusion analysis, the Mo absorber that needed higher EL for activation was not well explained. Lateral thermal flow should be considered to treat a high thermal conductivity film like Mo. Narrowing of process window against EL was attributed to the absence of reflectivity reduction mechanism.
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References

Fig. 1: Light penetration depth in Si and device dimension.

Fig. 2 Specimen structure and film thickness.

Fig. 3 Relationships between $E_L$ and sheet resistance. The TiN absorber decreased $E_L$ necessary for dopant activation, but Mo increased.

Fig. 4 Simulated melt depth against $E_L$ to discuss effectiveness of absorber.

Fig. 5 Sb depth profiles for various laser energy densities to compare process window width against $E_L$ for the no absorber case (solid line) and the TiN absorber case (dashed line).
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Shallow Junction Formation (< 20 nm)

Motivation

Shallow Junction Formation (< 20 nm)
RTA, Spike-RTA...

What is next?

- Solid phase regrowth: min to hr
- FLASH lamp: µs – ms
- CW Laser Annealing (Non-Melt): µs – ms
- Pulse Laser Annealing (Melt): ns

nanoseconds Laser Annealing is ultimate one to obtain non-thermal equilibrium

Selection of Laser Source

Shallow Junction Formation (<20 nm) KrF Excimer Laser

IJWT 2002 Kurobe et al.
Hiroshima Univ.

High Power Excimer Laser
Issues: Equipment size and maintenance

All-Solid-State Green Laser (λ: 532 nm)
Solutions for the issues

Penetration Depth

Penetration Depth
Green Laser (532 nm): 927 nm
KrF Excimer Laser: 5.5 nm

Wasting laser power!

Light Absorber
Shallow penetration depth

Requirements for Absorber

- Shallow penetration depth
- High thermal conductivity
- High thermal stability

Refactory metal or Barrier metal + Insulator

Candidates
- TiN
- Mo + SiO₂

Sample Structure

Green laser 120 ns
TiN: Reactive Sputtering
N₂/(N₂+Ar) 25% or 75%
60 or 120 nm
Mo: Sputtering 50 nm
SiO₂: 2 nm
Ge⁺: 3x10¹⁵ cm⁻²
5.10, or 15 keV
Sb⁺: 6x10¹⁴ cm⁻²
4.7, or 10 keV

Light Absorber
n⁺ diffusion layer
Si Sub.
Depth Profile: No absorber

- Junction depth is controlled by amorphization depth.
- \( E_L (\text{Laser energy density}) \) for melting > 1.3 J/cm\(^2\)

Depth Profile: TiN absorber

- \( X_j < 10 \text{ nm} \) is obtainable with absorber
- \( E_L \) for melting ~ 0.9 J/cm\(^2\) \( \leftarrow \) Reduced

Comparison of TiN and Mo Absorbers

- \( E_L \) for melting: TiN decreased, Mo increased

One-dimensional Thermal Diffusion Simulation

\[
\begin{align*}
\frac{\partial T(x,t)}{\partial t} & = \frac{\partial}{\partial x} \left( \kappa(T) \frac{\partial T(x,t)}{\partial x} \right) - \alpha(1-R)I(x,t) \\
\left. \frac{\partial T}{\partial x} \right|_{x=0} &= 0 \\
T_{x=L} &= T_0, \quad T_{t=0} = T_0
\end{align*}
\]

Comparison with Simulation

- TiN and No Absorber: Qualitatively explained by simulation
- Mo: Discrepancy

TiN and Mo

- \( E_L \) for Melt: Mo > No absorber
- Reflectivity (included in simulation)
  - Si: 38%
  - TiN: 30%
  - Mo: 58%
- Difference in reflectivity is not enough to explain

Thermal Conductivity

- Mo: 113 W/m/K >> TiN: 11 W/m/K \( @ \) 700°C
- Mo: Lateral thermal conduction should be considered
**Process Window Width**

**Experimental Results**

- TiN: Narrow process window against $E_L$ variation

**Influence of Reflectivity Change**

- c-Si, a-Si: Semiconductive $R=0.38$
- liquid-Si: Metallic $R=0.70$

**Origin of Narrow Process Window**

- Metal absorber: No stopping mechanism against c-Si overmelt

**Conclusions**

- Green laser annealing with light absorber Results
  - TiN $\Rightarrow E_L$ reduction, Mo: NG
    - Lateral thermal diffusion should be considered to explain this
  - Over-melt, narrow process window
    - Absence of feedback mechanism

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