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Development of Plasma CVD SiOx Hard-Coating for Transparent Injection-Molded Resin

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1. Introduction and Objectives

To extend the cruising range of electric vehicles (EVs), significant weight reduction of the vehicle body is essential. Replacing conventional inorganic glass with lightweight transparent polymers, such as polycarbonate (PC), can reduce component weight by approximately 30%. However, PC suffers from low scratch resistance compared to glass. While SiO_x-based hard coatings deposited via plasma chemical vapor deposition (CVD) offer a potential solution, they face two major technical barriers: micro-cracking due to internal stress in thick films (>1.0 µm) and poor adhesion/delamination under high-humidity environments. This research aims to overcome these "physical stress" and "chemical stability" challenges through a rational, theory-driven design approach to meet automotive reliability standards.

2. Innovation: Gradient Laminated Structure for Stress Relaxation

The originality of this study lies in achieving both high hardness and crack resistance by implementing a gradient laminated structure. Using a remote plasma CVD system (Shibaura Machine LPP-400TT), which maintains substrate temperatures below 80°C, a multi-layer film is deposited in a single continuous process by modulating the radio frequency (RF) power.

・Primer Layer: Deposited at a lower RF power (1500 W), this layer forms a flexible silicone-resin-like structure. It effectively accommodates the surface roughness of the PC substrate and absorbs internal stresses.

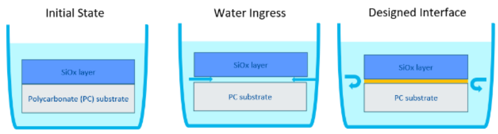
・Surface Layer: Deposited at a higher RF power (1800 W), this layer results in a high-density silica-like film that ensures superior scratch resistance.

3. Novelty: Thermodynamic Interface Design via Hamaker Constant

To address delamination, the study hypothesizes that peeling in humid conditions is driven by water ingress via capillary action. Instead of empirical trial-and-error, the researchers applied the Lifshitz theory-derived Hamaker constant (A_{132}) to model the thermodynamic stability of the interface. The adhesion energy Wad is directly related to A_{132}, calculated by the following expression:

$$A_{132} \approx \frac{3}{4}kT\left(\frac{\varepsilon_1-\varepsilon_3}{\varepsilon_1+\varepsilon_3}\right)\left(\frac{\varepsilon_2-\varepsilon_3}{\varepsilon_2+\varepsilon_3}\right)$$

$$+\frac{3h\nu_e}{8\sqrt{2}}\frac{(n_1^2-n_3^2)(n_2^2-n_3^2)}{(n_1^2+n_3^2)^{1/2}(n_2^2+n_3^2)^{1/2}\left\{(n_1^2+n_3^2)^{1/2}+(n_2^2+n_3^2)^{1/2}\right\}}$$



	Initial State	Water Ingress	Designed Interface
S1	SiO_x	SiO_x	SiO_x
S3	SiO_x	**Water**	**Nb_2O_5**
S2	PC	PC	PC
A_{132} (J)	**≈ 0 (Dry/Air)**	**1.8×10^{-20}**	**1.6×10^{-19}**

Fig.1 Schematic diagram and Hamaker constant (A_{132}) calculation results.

Fig. 1 shows a schematic diagram and calculation results. According to Fig 1, calculation results showed that the SiO_x/Water/PC system is more energetically stable than the dry state, providing a thermodynamic driving force for water ingress. To counteract this, niobium pentoxide (Nb_2O_5) was identified as an ideal interlayer material due to its high refractive index (n ≈ 2.3).

4. Results and Contribution to Automotive Engineering

Experimental validation confirmed the effectiveness of these dual strategies:

- Crack-Free High Hardness: The optimized 1.0 µm thick film achieved a pencil hardness of 3H without any visible cracking.
- Exceptional Durability: The introduction of a 5 nm Nb_2O_5 interlayer prevented delamination for over 250 hours in a 60°C hot water immersion test, a tenfold improvement over conventional structures which failed at 25 hours.
- Enhanced Productivity: Forming multi-layered films by simply switching power settings within a single CVD process simplifies manufacturing and reduces costs. By establishing a rational design guideline for interfacial engineering, this technology significantly promotes the adoption of sustainable materials and contributes to the realization of a circular economy in the automotive sector.