Magnesium Zinc Oxide Thin Film Deposition Effect on Selfheating Behaviour on Solar Panels for Hybrid Solar Vehicle

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**Abstract:** The significance of electric vehicle (EV's) technology finding potential for transportation applications and has unique characteristics, including eco-friendly, pollution-free, and economical compared to fossil fuel. The silicon nitride (SiNx) layers are beneficial for certain applications, such as surface passivation and antireflection in solar cells. However, using them alone has significant drawbacks, including variations in transistor behaviour and electrical properties across the solar spectrum. To address these issues, the present research is exploring hybrid coating like magnesium-zinc oxide (Mg-ZnO) doping with SiNx layer via plasma chemical vapour deposition route with radio frequency magnetron route under 100 ºC temperature with 13.56 MHz. Influences of processing and Mg-ZnO actions on microstructural (scanning electron microscope & X-ray diffraction), transistor drain current, and photocurrent density behaviour of SiNx layer and SiNx layer featured with Mg-ZnO layer. Microstructural studies revealed that the particles are dispersed uniformly, and XRD peaks conform to the intensities of Mg, ZnO, and SiNx layers. The significance of the Mg-ZnO layer found better carrier mobility and photocurrent density than SiNx. The self-heating effect of Mg (ZnO) film was investigated, and its electrical input and output behaviour was studied. Evaluated results of this research showed 1.01 cm2/volts carrier mobility with increased photocurrent density of 2.4 mA/cm2 and on/off current ratio found as 10-5.

# Introduction

Solar renewable energy is prospective for various applications, including solar heaters, solar-based heat exchangers, solar-based hybrid electrical vehicles, etc [1-3]. With technological growth, solar-based hybrid electrical vehicles have the potential for automotive EV applications due to their significant eco-friendly behaviour, better efficiency, and zero pollution compared to fossil fuel [4-8]. The photovoltaic self-heating performance is enhanced by way of zinc oxide-based semiconductor thin film coating made by the chemical vapour deposition route [9-11]. However, the conventional solar PV cell doped with advanced material found better thermal, electrical, and optical behaviour compared to the conventional film layer [12-13] investigated solar cell performance by featuring ZnO nanostructure acting as a semiconductor, which enhances the solar cell's electrical efficiency and leads to better optical/thermal behaviour related to conventional solar cells. The titanium dioxide featured zinc oxide nanocomposite thin layer is formed for solar energy operated photocatalysis application. The zinc oxide and titanium dioxide are evenly dispersed and make better optical and electrical behaviour. The excellence of the ZnO layer influences better thermal stability and increased electrical energy related to monolithic solar panels (Prasannalakshmi and Shanmugam 2017). However, the ZnO nanostructure solar cell exposed superior thermal behaviour as well as improved thermal stability, resulting in better electrical and thermal efficiency. Based on the doping technique, the solar cell layer performance is varied and nano-sized film influences superb PV performance [14-16]. Recently [17-21], they reviewed the effect of a ZnO-based coating layer on the functional characteristics of solar cells. They reported that the ZnO layer over the solar cell offered high transparency, thermal and chemical stability, and significant improvement in electrical conductivity behaviour.

Moreover, the selection of doping material, processing for doping materials, and its process parameters may influence better coating, resulting in a superior band gap, better antireflection coating, and unique behaviour [22-23] utilized ZnO nanorods with varied concentrations of Nd and Ag, which act as hetero-junction solar cells. Effects of ZnO doping on structural, optical, and morphological characteristics are studied. The ZnO is exposed to better I-V performance with improved optical behaviour. However, the hybrid thin film coating performed better transparent conducting oxide (TCO) layer and exhibited high electron mobility. With this, the Ga with MgX Zn1-X O buffer-based solar cell was experimentally studied, and it was reported that the CdTe solar cell was distributed uniformly [24-25]. However, the choice of TFT with Mg (ZnO) doping showed a reduced band gap, which resulted in an increased self-heat effect of solar cells, and a large gap found a defective surface, which led to a reduction in the behaviour of solar performance [26-27]. The ZnO-based heterostructures are found to have better electrical behaviour and are recorded by optimum TCO [28]. He prepared twin thin films, namely gallium and zinc oxide, configured with a SiNx layer for solar cell applications [29].

The excellence of twin thin film influences better optical transmittance and improved photocurrent density properties, which is better than the monolithic SiNx layer. Moreover, the adaptations of the modified damping system in solar cells were found to minimize the degradation of solar energy, which leads to superior optical and J-V performance [30-32]. Recently, black chromium-coated solar receivers have had the potential to improve solar light absorption and lead to better enhancement in the thermal and electrical behaviour of solar systems (Sathish 2020). However, photovoltaic features with dynamic modules with varied vibration frequencies provide better functional characteristics and lead to enhanced photocurrent density properties [33-35]. They developed a SnZrO3 doped PS-based solar cell, which has better electrical properties, and the presence of the SnZrO3 layer leads to improved solar conversion efficiency behaviour. The additions of silicon carbide porous material enhance the solar photovoltaic system's optical and electrical properties. The silicon carbide porous material provides and balances the solar radiation. It leads to superior thermal, optical, and electrical properties [36-38]. With additions, the silicon thin film featured a Cadmium Telluride Solar Cell able to endure the optimum current conduction, improved optical behaviour, and better quantum efficiency compared to an uncoated Cadmium Telluride Solar Cell (Singh and Bashir 2025). The thin film technology is assuring better electrical and optical behaviour with improved electrical conduction behaviour [39].

Current research related to past literature is studied, and the silicon nitride (SiNx) layer is found to have significant properties like antireflection and surface passivation behaviour, leading to better solar absorption and antireflection properties. However, the mono SiNx layer has found challenges in variation in current density and carrier mobility. The research objective is enhancing the carrier mobility, photocurrent density, and microstructural behaviour of the SiNx layer, which is featured with 30nm of Mg-ZnO layer via plasma chemical vapour deposition method using a radio frequency magnetron at temperatures below 100 ºC and a frequency of 13.56 MHz. Processing effect on microstructural and actions of Mg-ZnO on drain current and photocurrent properties are evaluated, and its outcome is compared with the results of the SiNx layer. The novelty of the present research is that better carrier mobility with improved drain current and better photocurrent density due to better particle dispersion.

# Materials and Methods

Before the fabrication process, the SiNx layer is cleaned ultrasonically with acetone for 10min and dry the substrate via nitrogen gas. After the process, the surface is involved in a pre-treatment process with plasma, which helps to enhance the adhesion behaviour [40-41]. The 65-85nm thickness of the SiNx layer was found to have better functional behaviour. The cleaned SiNx surface is kept in the reaction chamber and fixes the base pressure of 1X10-6 pa. The 10:90 weight percentages Mg and ZnO were utilized as radio frequency magnetron material with 80watts power under 100ºC. During the process, the Mg-ZnO is separate like MgO and ZnO targets for co-sputtering. The argon inert gas is used for primary sputtering gas, which is 30sccm. The indium oxide was layered over the glass. After the process, the plasma chemical vapour deposition route was adopted with a SiNx film layer under 65 nm (thickness) formed at the pressure of 1 Pa with 50w power, identified from Fig. 1. The radio frequency (13.56 MHz) magnetron helps to maintain the layer thickness. Moreover, this layer attempts to 100ºC, which helps to increase the particle distribution and reduce the space between the particles [42-44]. During the deposition process, the temperatures of the film are monitored via thermocouple setup and the plasma sputtering the Mg-ZnO for 30min. Rotate the SiNx layer and ensure the even Mg-ZnO particle distribution. A lower heating effect of 100ºC formed the layer. The thin film of 30nm of Mg (ZnO) dope formed by sputtering subjected to a photo-resist coat enhanced solar irradiance behaviour compared to conventional film [45].

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Figure 1 Plasma chemical vapour deposition route with radio frequency magnetron.

Finally, the substrate allows cooling at ambient temperature with argon inert atmosphere, which leads to minimizing the thermal stress. The Mg (ZnO) deposition layout is noted in Figure 2 and has a 50nm film thickness.

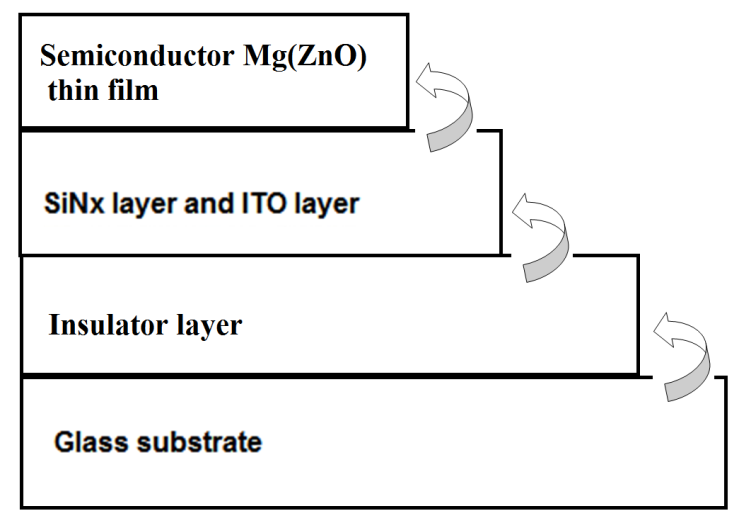


Figure 2 Mg (ZnO) - doping system (film -50nm thickness).

The ZESIS-made Sigma 360 model scanning electron microscope is used to analyze the developed Mg-ZnO doped SiNx layer. With the help of an X-ray diffraction machine, the intensity of the doping layer is analyzed and based on Bragg's Law, the crystal planes to diffraction angle are measured. The drain current behaviour of the Mg-ZnO doped SiNx layer was measured by using the equation 1 and 2 as follows [46].

(1)

Where µ is the carrier mobility in the Mg-ZnO layer, Cox is the gate oxide capacitance per unit area, W is the channel width, L is the channel length, VGS and VDS are the gate-to-source and drain-to-source voltage, and Vth is the Threshold voltage.

Likewise, the photocurrent density behaviour of thin film is presented in equation 2 [47] as follows.

(2)

Where Iph is the photocurrent, q is the elementary charge, G is the photon generation rate per unit volume, and ղint is the internal quantum efficiency.

During the measuring of drain current and photocurrent density behaviour of SiNx and Mg-ZnO layer featured SiNx layer, the experiments are repeated three times with a statistical significance of 5% considered. Based on the system reproducibility of the experiments, the error significance is fixed and not more than 5%. Based on the three trains, the average values of outcomes are ensured and taken as actual values.

# Results and Discussion

Fig. 3(a-b) illustrates the SEM for the Plasma chemical vapour deposition route with radio frequency magnetron developed Mg (ZnO) solar film. The polycrystalline grain structure with finer grains enhanced the absorption behaviour under a low thermal effect. Fig. 3 (a) shows that the Mg (ZnO) has uniformly spread along the SiNx layer because of the impact of lower temperature deposition with the radio frequency magnetron technique. The plasma chemical deposition technique found superior layer formation and maintained the film thickness throughout the lamina. Based on the depositions of Mg (ZnO), the layer side view is illustrated in Fig. 3(b). The excellence of low-temperature processing influences better particle dispersion and leads to improved carrier mobility [48].

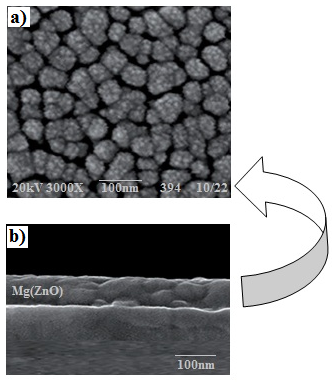


Figure 3 SEM images of a) Mg (ZnO) layer b) Mg (ZnO) grains.

Fig. 4 represents the X-ray diffraction pattern image of the Mg (ZnO) layer. It shows the variation peaks like ZnO SiNx/Ito layers. No secondary phase was identified during the analysis of X-ray diffraction images. Processing actions with applied constant frequency influence better particle distribution and lead to better electrical properties. The ZnO (003) peak was noted by 37.1º continued that corresponding peaks were formed. The SiNx showed 45.2º (007), and the Mg peak is found at (60.7⁰). The above Fig. 4 proves the presence and deposition effect of Mg (ZnO) on the SiNx layer. The intermediate gap shows the particle space. Even peaks of the ZnO layer with alternative Mg peaks after the SiNx layer show better intensities and lead to better functional properties. The even dispersion of Mg-ZnO particles in the SiNx layer has the potential for improved carrier mobility and better photocurrent density. With additions, the absorption behaviour layer is progressively enhanced than the Mono SiNx layer.

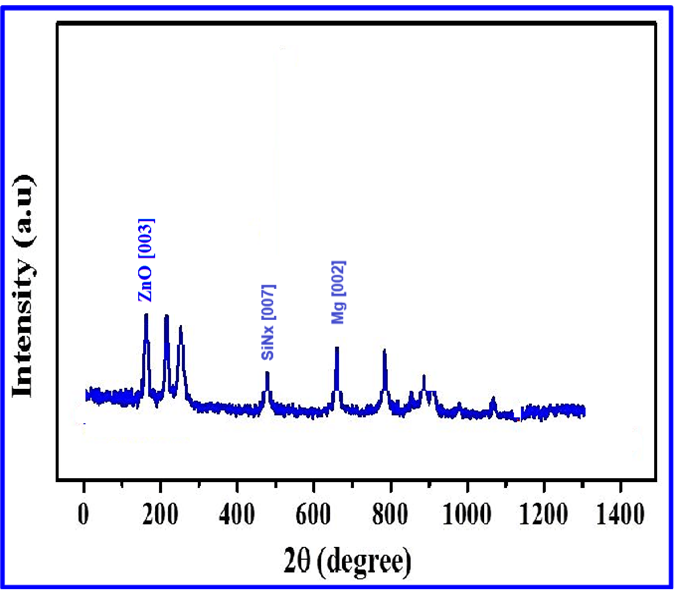


Figure 4 X-ray diffraction pattern for Mg (ZnO).

According to Figure 2, the mean value of WR is 0.0031 and was shows that the U, V, and W are 3.81N, 8.2m/s, and 2050m, respectively. During the evaluation, WR is chosen as smaller is better.

The thin film transistor behaviour of the Mg (ZnO) layer on SiNx is presented in Figure 5 and measured between drain voltage (Vd) Vs drain current (Id). The varied gate voltage, including from 0 to 12 volts, and the curve of Fig. 5 showed the conductance didn't meet the lower current output. It was attained by introducing the Mg (ZnO) thin layer, and its cross-section image for Mg (ZnO) is indicated in Fig. 6.

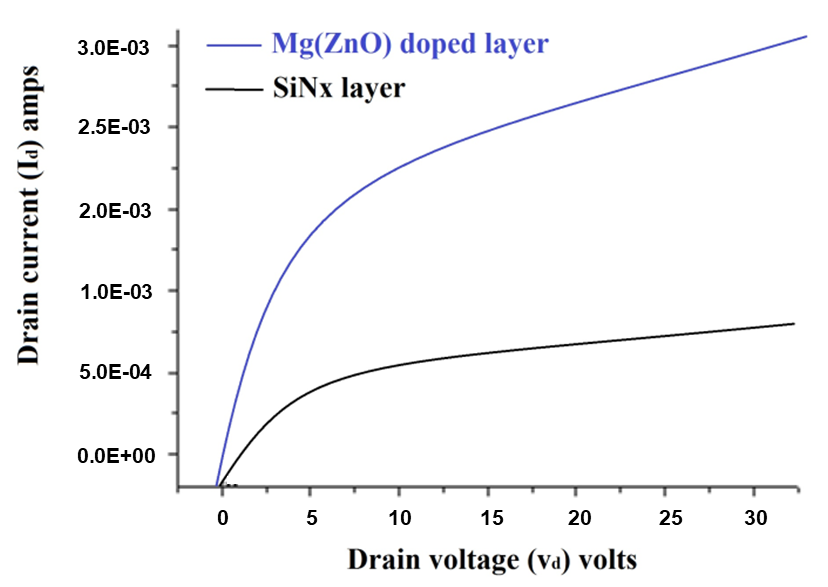


Figure 5 Effect of Mg (ZnO) on drain current vs. drain voltage of solar film.

The above Fig. 5 shows the variations in drain current concerning drain voltage. The Mg (ZnO) doped SiNx solar layer was found to have a higher current than the SiNx layer. So, the drain current was improved by the presence of the Mg (ZnO) layer in SiNx. It was due to fine grain boundaries with the intrinsic self-heat effect of Mg (ZnO) material. The ZnO offered good self-heating compared to conventional layers. The doping of Mg-ZnO enhances current flow by reducing the resistivity of the layer, especially when an electric field is applied. This results in an increased drain current. The lower series resistance of the device further improves the drain current and promotes more efficient carrier movement. Together, these factors enable greater current flow and more effective charge transfer, making Mg-ZnO-doped SiNx layers highly advantageous for advanced applications in solar cells, optoelectronics, and transistors. However, the drain current behaviour is 12% and 5.3% better than the RF sputtered Mg-ZnO layer and gallium-ZnO doped SiNx layer [23].

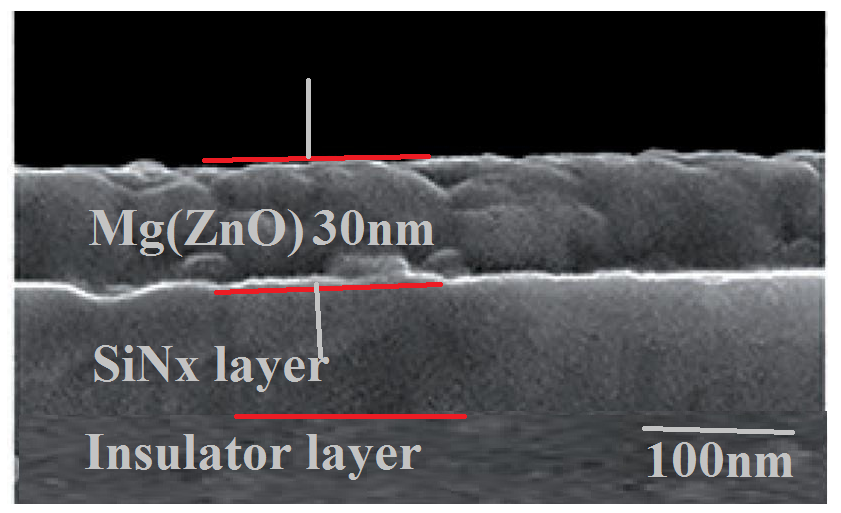


Figure 6 Cross-section solar film coated with Mg (ZnO) layer.

The Enlarged Mg (ZnO) particle structure is displayed in Figure 7. It clearly shows the particle space and doping position. Due to this layer, we found the 1.01 cm2/volts carrier mobility with an increased photocurrent density of 2.4mA/cm2 and an on/off current ratio of 10-5. The details of photocurrent density are shown in Fig. 8.

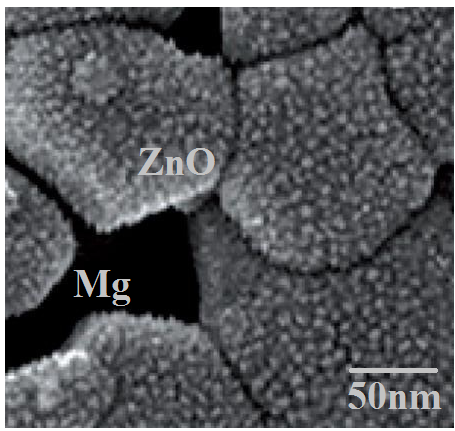


Figure 7 Doping Mg (ZnO) particle enlarged structure.

Fig.8 illustrates the Mg (ZnO) behaviour of SiNx solar cells with 30nm. It showed a significant improvement in photocurrent density on the improved voltage of 0.2 volts. Moreover, the curve showed the enhancement of the SiNx layer with Mg (ZnO) coating. The blue line of Fig. 8 illustrates the photocurrent density of Mg (ZnO), and the block curve indicates the SiNx without coating material. However, the photocurrent density was improved by 2.4mA/cm2, and the on/off current ratio was 10/5. The above graph is the evidence for enhancement of photocurrent density on Mg (ZnO) doping with SiNx and found a 50% improvement in photocurrent density compared to SiNx solar cell. Enhancing solar cell photocurrent density was due to the ZnO layer offering a good self-heat effect at lower temperatures. A similar tendency was reported by researchers [47-48].

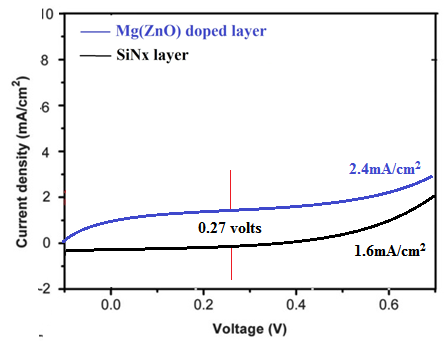


Figure 8 Effect of Mg (ZnO) on photocurrent density of solar film.

Because Mg-ZnO has greater electron mobility than SiNx, photogenerated carriers can be transported with less recombination and scattering. Mg-ZnO doping reduces the recombination of photogenerated carriers at the interface or in bulk by passivating the defect states found in the SiNx layer. The photocurrent density rises as more carriers become accessible for collection. However, the Mg-ZnO featured SiNx layer has optimum photocurrent density behaviour and was found to be 9% and 4% better than the RF-sputtered Mg-ZnO layer and gallium-ZnO doped SiNx layer [49-51].

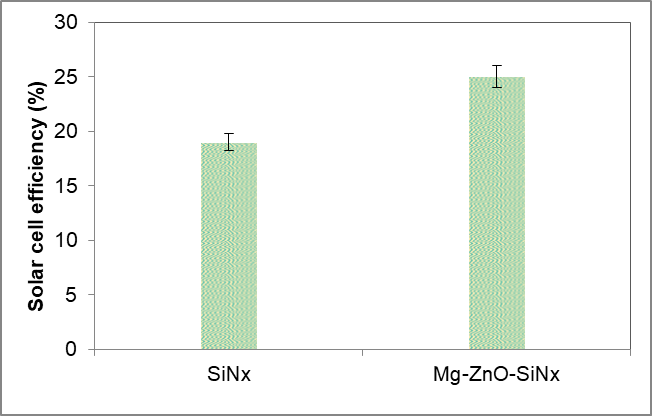


Figure 9 Effect of Mg (ZnO) on solar cell efficiency of solar film.

Fig.9 indicates the solar cell efficiency of the SiNx and Mg-ZnO doped SiNx layer. The solar cell efficiency of SiNx is found to be 19%, which is lower than the Mg-ZnO doped SiNx layer. SiNx improves the amount of light that penetrates the cell by reducing light reflection, particularly in the visible spectrum. With the significance of reduced light reflection, the current generation is increased. At the same time, the SiNx featured with the Mg-ZnO layer has the potential for high solar cell efficiency properties, which is 25% and higher than the SiNx behaviour. By providing better surface passivation and lowering surface recombination, the hybrid layer may enhance the overall function of the cell. When compared to the normal SiNx layer, the Mg-ZnO doped SiNx layer offers a better potential efficiency (32% better than SiNx) because of its improved surface passivation capabilities, optical transparency, and better carrier capabilities.

# Conclusion

The SiNx layer is featured with magnesium/zinc oxide (Mg-ZnO) coating via plasma chemical vapour deposition route with radio frequency magnetron technique followed by 100ºC with 13.56 MHz frequency. With the actions of Mg-ZnO doping and processing on microstructural behaviour, including scanning electron microscope (SEM) and X-ray diffraction analysis, transistor behaviour (drain current) and photocurrent density behaviour of Mg-ZnO doped SiNx layer is studied, and its outcomes are compared with undoped layer. Based on the result outcomes, the important conclusions are summarized below.

SEM images provide the clear structure of Mg-ZnO doping with SiNx, and the particles of Mg-ZnO are evenly dispersed with the SiNx layer, resulting in improved transistor and photocurrent density behaviour. The gap between the Mg-ZnO is low and widely dispersed with the SiNx layer, resulting in improved functional behaviour and favours better absorption properties.

Likewise, the XRD pattern provides the even peak intensity of ZnO in the SiNx layer and influences better functional characteristics.

With the significance of the Mg-ZnO layer in the SiNx layer, better transistor properties and optimum drain current value are found, which is 60% better than the SiNx layer performance.

Likewise, the photocurrent density property of the Mg-ZnO doped SiNx layer has a superior value and is 33.3% better than the SiNx layer without the Mg-ZnO layer. The structure was recommended for advanced solar cells in solar-operated electrical vehicle applications.

Future studies will execute different thicknesses of electron transport layers like SiO2 ZnO with copper back contact on the functional behaviour of SiNx and compare the results for better EV performance.

This technology has the potential to significantly enhance battery efficiency and reduce heat losses, particularly in next-generation lithium-ion systems. This improvement could facilitate the integration of these batteries into commercial hybrid electric vehicles (HEVs). However, two major challenges in scaling up for mass production are maintaining cost-effective manufacturing processes and ensuring compatibility with various vehicle architectures. To address these challenges, advancements in material optimization and collaborative pilot programs with automakers are essential. Future research should focus on refining production methods and minimizing environmental impacts to ensure the seamless integration of this technology into HEVs.

Both magnesium and zinc oxide are recyclable, making the recyclability of Mg(ZnO) films promising. However, it is important to develop effective recycling procedures to address potential bonding and interaction issues among the components. Advancements in separation and recovery methods, particularly those that emphasize energy efficiency and minimize material degradation during use, are crucial for the future recyclability of Mg(ZnO) films.

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