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Catalysis & Surface COMMENTARY

The Innovation Materials

Lighting the way to ethylene from CO_2

Jianheng Xu,[1,2] Liangliang Jiang,[3] Zeshu Zhang,[1,2,*] Xiangguang Yang,[1,2] and Yibo Zhang[1,2,*]

[1]Ganjiang Innovation Academy, Chinese Academy of Sciences, Ganzhou 341000, China

[2]School of Rare Earths, University of Science and Technology of China, Hefei 230026, China

[3]Department of Chemical and Petroleum Engineering, University of Calgary, Calgary, Alberta T2N 4 V8, Canada

*Correspondence: zszhang@gia.cas.cn (Z.Z.); yibozhang@gia.cas.cn (Y.Z.)

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Turning CO_2 into value-added fuels and chemicals remains one of the most urgent challenges in the era of global warming. Rising atmospheric CO_2 levels—projected to exceed 590 ppm by 2100 according to the IPCC (The Intergovernmental Panel on Climate Change)—underscore the pressing need for transformative carbon management strategies. Conventional catalytic routes have succeeded primarily in generating single-carbon (C1) products such as CO, formate or methanol. However, these compounds have limited industrial impact compared with C2+ hydrocarbons, which are central to the global economy. Ethylene, in particular, is indispensable as the feedstock for polymers, solvents, and pharmaceuticals, with an annual market exceeding hundreds of millions of tons. Achieving its selective synthesis directly from CO_2 has remained an unsolved challenge because of the intrinsic thermodynamic stability of CO_2 and the kinetic difficulty of forming C–C bonds.[1] Conventional thermocatalytic processes (steam cracking of petroleum or natural gas) typically required high temperatures (> 800°C), which activate multiple pathways and lead to a statistical distribution of products rather than selective conversions. Therefore, developing an alternative route that combines mild operating conditions with high selectivity has long been a regarded as a central challenge in CO_2 utilization research.

Jin and co-workers report a distinct strategy for CO_2 conversion based on photochemical H_2 dissociation at ambient temperature over Au/TiO_2, achieving nearly quantitative conversion to ethylene via a $CO_2 \rightarrow C_2H_6 \rightarrow C_2H_4$ cascade.[2] Unlike conventional thermocatalysis that relies on homolytic H_2 splitting into neutral radicals, ultraviolet irradiation (365 nm) at the Au/TiO_2 interface induces interfacial dipoles resembling frustrated Lewis pairs. As shown in Figure 1, photogenerated electrons accumulate on Au nanoparticles, while holes are trapped at interfacial Au–O–Ti sites, creating localized charge centers separated by only a few nanometers. The authors propose that these spatially separated charges promote heterolytic H_2 dissociation, generating nucleophilic $H^{\delta-}$ species on Au surfaces and $H^{\delta+}$ species associated with interfacial oxygen. Subsequent CO_2 hydrogenation proceeds via surface-bound intermediates, with C–C bond formation occurring predominantly on Au. This charge-driven mechanism accounts for the exceptional selectivity observed under mild conditions. Catalyst stability is further enhanced by a light-induced TiO_x overlayer on Au nanoparticles, which suppresses sintering and migration through strong metal–support interactions while modifying the interfacial electronic structure. As a result, CO_2 is reduced to ethane with over 99% selectivity, followed by photocatalytic dehydrogenation to ethylene, maintaining >99% selectivity for more than 1500 hours of continuous irradiation. This combination of high selectivity and durability represents a significant advance in photocatalytic CO_2 conversion.

The implications of this work are substantial. Mechanistically, it challenges the long-standing view that efficient H_2 activation for CO_2 reduction requires either high-temperature homolytic dissociation or carefully designed surface acid–base pairs.[3,4] Instead, Jin et al. demonstrate that light can directly drive heterolytic pathways under mild conditions. Conceptually, this shifts the paradigm from thermal bond activation toward engineering interfacial charge distributions using light. Practically, the system uniquely combines high selectivity, long-term stability, and mild operating conditions. The dual function of the TiO_x overlayer as both electronic mediator and structural stabilizer

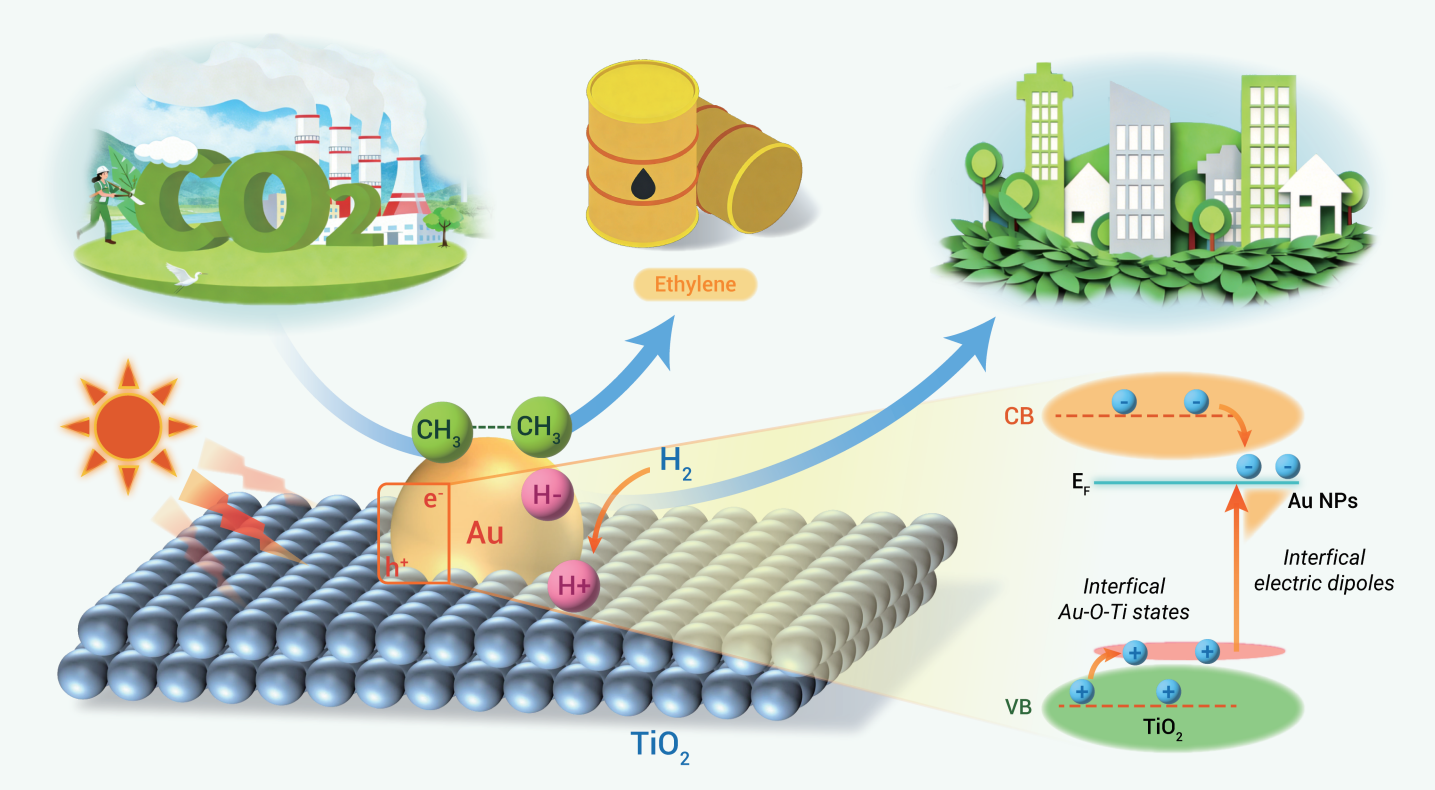

Figure 1. The scheme of photocatalytic CO_2 hydrogenation to ethylene.

highlights the potential of dynamic surface engineering. More broadly, if light-induced interfacial dipoles can be extended to other reactions, this principle may enable new strategies for nitrogen fixation, selective hydrocarbon upgrading, and biomass valorization, where hydrogen activation often represents a bottleneck.

Despite the remarkable achievements of Jin et al. several critical challenges remain before light-driven CO_2 hydrogenation can move from laboratory demonstration to practical application.

1. Energy efficiency bottleneck: The current system relies on UV light (365 nm) to excite TiO_2, which represents only ~5% of the solar spectrum. Although apparent quantum efficiencies approaching ~58.5% have been achieved at the reaction level under optimized conditions, the overall solar-to-chemical efficiency is inherently constrained by the reliance on high-energy photons and the 14-electron nature of the CO_2-to-C_2H_6 transformation. Notably, the original study reveals a pronounced wavelength dependence in reaction behavior: UV irradiation primarily drives charge separation and heterolytic H_2 dissociation, whereas visible-light excitation introduces plasmonic and photothermal contributions that lead to distinct product distributions. This wavelength-selective behavior underscores that energy efficiency and reaction selectivity are tightly coupled to the underlying excitation mechanism. Improving energy utilization will therefore require not only extending light absorption into the visible region, but also ensuring that lower-energy photons can effectively sustain charge-driven pathways. Potential strategies include enhancing photo–thermal synergy, employing light concentration techniques, and developing catalysts that operate efficiently under visible light through bandgap engineering, plasmonic enhancement, or defect-state modulation to broaden absorption and strengthen charge separation.

2. Scale-up and reactor design: The reported results were obtained in a laboratory-scale flow system driven by external LEDs. Scaling up will require addressing light distribution, heat accumulation, and reactor uniformity challenges. Future designs may benefit from fiber-optic or photothermal fixed-bed reactors that couple light and reaction zones efficiently. Structured reactors, photonic materials, or solar concentrator-assisted systems may help bridge laboratory demonstrations with scalable processes. Furthermore, life-cycle assessment (LCA) and energy return on investment (EROI) analyses will be essential for evaluating system-level feasibility.

Despite these challenges, the concept of light-induced heterolytic H_2 dissociation at Au–TiO_2 interfaces represents an emerging conceptual in CO_2 conversion chemistry. This breakthrough not only redefines how hydrogen activation can be achieved photochemically but also opens opportunities to integrate materials design, photochemical control, and reactor engineering toward practical, solar-driven CO_2 utilization and sustainable carbon management.

● Toward visible-light utilization and theoretical insights

Future studies should aim to extend photoresponse into the visible and near-infrared regions through bandgap tuning, plasmonic coupling, or defect engineering. Combining these catalysts with solar concentrators or hybrid photovoltaic–photocatalytic systems could greatly enhance overall solar energy conversion efficiency. Although experiments confirmed the role of interfacial electric dipoles in H_2 splitting, the ultrafast dynamics of electron–hole pairs and their coupling to H_2 and CO_2 remain to be clarified. Time-resolved spectroscopy, operando synchrotron techniques, and first-principles simulations can reveal transient charge-transfer pathways and guide rational catalyst design. At the same time, rigorously disentangling photochemical and photothermal effects in hybrid plasmonic systems remains a critical methodological challenge, underscoring the need for standardized experimental protocols and diagnostic criteria to ensure reliable mechanistic interpretation.[5]

● Expanding cascade reactions and integration into renewable energy systems

The demonstrated cascade reaction from $CO_2 \rightarrow C_2H_6 \rightarrow C_2H_4$ provides a prototype for multi-step CO_2 valorization, future research could incorporate multifunctional catalytic modules to selectively produce other C2+ chemicals —such as ethanol, propylene, or acetic acid—thus advancing the concept of an integrated CO_2 refinery. For practical implementation, such cascade systems should be coupled with renewable hydrogen generation and carbon capture technologies, forming a closed CO_2–H_2–C_2 chemical cycle powered entirely by clean energy. Modular reactor designs featuring distributed LED or solar illumination could further enhance efficiency and scalability, while techno-economic and life-cycle assessments will be essential to evaluate long-term sustainability and guide real-world deployment.

● Toward a carbon-neutral future

Beyond this specific system, the photochemical H_2 dissociation mechanism offers a new kinetic pathway for coupling light, hydrogen, and carbon cycles. Its conceptual impact extends to other energy-intensive transformations—such as ammonia synthesis and CO_2–CH_4 co-conversion—potentially forming the scientific foundation for next-generation carbon-neutral energy systems.

In summary, the contribution of Jin and colleagues represents more than a technical breakthrough—it provides a conceptual framework for the future of light-driven catalysis. By harnessing photochemical hydrogen dissociation at engineered Au/TiO_2 interfaces, they have not only demonstrated a near-ideal combination of activity, selectivity, and stability in CO_2-to-ethylene conversion. The findings highlight the transformative potential of interfacial design and light-driven processes in addressing global challenges of carbon management. Looking ahead, efforts to optimize catalyst structures, improve light utilization, and integrate with scalable reactor technologies will determine how quickly such breakthroughs can move from the laboratory to real-world impact. Yet the central message is unambiguous: light, when carefully coupled to interfacial chemistry, can achieve what heat alone cannot. This principle may ultimately redefine how we design catalytic systems, guiding the transition toward a greener and more selective chemical future.

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AUTHOR CONTRIBUTIONS

J. H. Xu wrote the draft. L. L. Jiang helped draw the figure. X. G. Yang helped polish the language. Z. S. Zhang, Y. B. Zhang supervised and revised the manuscript.

DECLARATION OF INTERESTS

The authors declare no competing interests.