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Quantum Confinement Effects In Self-Assembled Perovskite Nanofilms For Room-Temperature Spintronics

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Abstract: *Potential next-generation electronic applications The combination of these unique quantum confinement effects and optoelectronic tunability has rendered perovskite nanofilms a promising type of next-generation electronic applications. The given work examines the role of quantum confinement in self-assembled organometal halide perovskite nanofilms and tests their applicability to spintronic uses at room temperatures. We constructed well-ordered nanofilms of methylammonium lead halide (MAPbX 3 ; X = Cl, Br, I) using a solution-phase synthesis strategy combined with atomic layer deposition methods and high-resolution electron microscopy. We attained comparable thin films, with thickness in the 520 nm span. The photoluminescence spectra, energy-dispersive X-ray spectroscopy (EDX) and magnetoresistance measurements were performed to measure the band gap shifts and shift in the spin coherence, and the magnetic field response. The motion picture took place on the indices of blue shifts in bandgap energies against decreased thickness, displaying the fact of strong quantum confinement. Besides, spin-polarized transport and anisotropic magnetoresistance in ultrathin MAPbI 3 films were also detected, signifying strong spintronic properties in the ambient. Such results indicate that controlled synthesis of perovskite nanofilm with engineered dimensionality and strain engineering may offer an expedient route to highly cost-effective, low-power spintronic devices. This article sheds light over the structural, electronic and magnetic coupling of confined perovskite layers and presents a framework to integrate them in nanoscale spin-based transistors and memory systems.*

Keywords: *Quantum Confinement, Perovskite Nanofilms, Spintronics, $MAPbI_3$, Room-Temperature Magnetoresistance, Bandgap Engineering, Self-Assembly*

I. INTRODUCTION

The convergence of the quantum materials research and the spin-based engineering of devices in recent recent years, gave rise to the phenomenon of spintronics, which promises new era of electronic applications. Spin based electronics (spintronics) tries to take advantage of not only the charge, but also the inherent spin of electrons so as to further functional performance, minimise energy use and to raise the rate at which computing is applied. Although in conventional semiconductor-based spintronic devices, diluted magnetic semiconductors and ferromagnetic metals are frequently used, more recently interest has arisen in hybrid materials with quantum confinement properties. Of them, organometal halide perovskites have elicited particular interest because of their extraordinarily high optoelectronic performance, superior carrier lifetime, and compatibility with low-temperature solution procedures. Within the perovskite nanostructures, especially methylammonium lead halides (MAPbX 3, X = I, Br, Cl), they provide a new opportunity to discuss quantum confinement on a nanoscale. As the physical size of these materials, in particular the film thickness, become of the order of the Bohr exciton radius, quantum confinement effects induce changes in the electronic band structure with tunable bandgaps,

electronic charge carrier dynamics behaviors and potential increase of spin polarization. It has a wide-ranging implication in its use in the light-emitting diodes (LEDs), lasers, field-effect transistors, photodetectors, and recently, since current evidence proving it (as of August 2014) is still limited, in room-temperature spintronic devices. The most dominant facilitating aspect in quantum devices working on perovskites is that they assemble themselves into nanofilms of correct thickness and crystallinity. Through precise control of synthesis parameters e.g. precursor concentration, solvent engineering, annealing temperature and choice of substrate, well ordered nanofilms with thicknesses of a few nanometers to tens of nanometers can be obtained. These movies do not only display quantum size effects, but also strong spin-orbit coupling (SOC) because of the correct existence of heavy metal cations, such as lead, and Rashba-Dresselhaus-style spin splitting by presence of structural asymmetry. These properties make them well suited to the creation, control and sensing of spin-polarized currents without the need to provide external magnetic fields, a major requirement in practicable applications of spintronic devices. The dependence on cryogenic temperatures is a serious obstacle to spintronics: many spintronic phenomena are only accessible at low temperatures. Nevertheless, perovskite materials have also shown intrinsic spin coherence and long spin lifetimes even under ambient condition, owing partly to the shortened spin relaxation channels and their exceptional defect tolerance. Theoretical work and experimental demonstrations in the recent past have pointed towards the possibility of perovskite nanofilms to be used as either spin filters or as spin valves or even as conducting spin halves. Further, in combination with ferromagnetic or topologically active layers perovskites may cause spin-dependent interactions via proximity effects. Such prospects present a route to new low-dimensional, solution-processable spintronic device concepts that are not scale-limited by the epitaxy of the heterostructures involved. In spite of the prospect, there are a number of issues that are still confronted. Among the most prominent concerns is the environmental insecurity of perovskites, in particular, the ones that contain the iodide-based halogens. Film morphology degradations may accompany loss of spin-active behavior by exposure to moisture, oxygen, and UV light. Moreover, the ultrathin lay of perovskite films with a uniform morphology, graded defect density, and even boundary necessitates thorough control over the deposition methods including spin coating, blade coating, or vapor-enabled crystallization. To combat these issues, numerous solutions have been put forward to control them, encapsulation with 2D materials (e.g. graphene), cation design, polymer additives, and a mixture of halide compositions to improve stability within the perovskite lattice and quantum and spin characteristics. The work seeks to explore the quantum confinement effect in self-assembled MAPbX 3 nanofilms and assess their room temperature application in spintronic. We investigate the effect of the dimensional confinement on bandgap energies, carrier mobility, and spin coherence by synthetically structuring nanofilms of controlled thickness and making direct measurements of photophysical, structural and spin transport parameters. In particular, the relationship between film thickness and change of the bandgaps is investigated through the photoluminescence (PL) spectroscopy and the spin-polarized response due to the current is determined with Mg-based magnetoresistance measurements which are averaged over different magnetic fields. The paper also utilizes scanning electron microscopy (SEM), atomic force microscopy (AFM) and X-ray diffraction (XRD) to describe the surface morphology, film uniformity and crystalline phases respectively. The primary driving force of the study is to be able to justify the existence of quantum confinement effect in perovskite nanofilms, as well as to prove that it is functional with respect to its performance as a room-temperature spintronic material. Since the outer shell portion of a perovskite atom is a quantum-confined perovskite, our results help us understand the fundamental physics behind quantum-confined perovskite spin-polarized transport and allows us to be able to design such material as the basis of future spin-based logic, memory and optospintronic devices. Combining quantum material science with device engineering, this work is also relevant to the frontier in spintronics and demonstrates the hybrid nanostructured materials are of interdisciplinary importance to the field of advanced electronics.

II. RELEATED WORKS

The combination of quantum confinement and spintronics has also become a very high-profile (it can really transform nanoscale electronic and information processing technologies)-area of interest. Extensive

literature has discussed the effects of quantum confinement of the charge transport and spin behaviour in low dimensional systems like quantum wells, nanowires and nanofilms. Due to the recent popularity of hybrid perovskite materials, especially the methylammonium lead halide compounds (MAPbX 3), interests have grown in their size-dependent behaviors, and their potential impact upon spintronics. Among the first principles on which quantum confinement occurs in perovskites, Tanaka et al have revealed that excitonic enhancement in layered perovskite structure can be achieved because of the quasi-2D structure of perovskites [1]. Later it was extended by the Perkins group creating nanofilms of MAPbI 3 and observing below 20 nm film thickness photoluminescence blue shifts which was attributed to spatial confinement, that is narrowing the optical bandgap [2]. The same results can be found in cesium lead bromide (CsPbBr 3) nanocrystals, where a bandgap tunability by size and an increased exciton binding energy could be reported [3]. Early studies have tended to be focused almost entirely on the optical nature of confined perovskites, but newer work has also started to focus on the magnetic and spin aspects. The Rashba spin splitting in non-centrosymmetric MAPbI 3 perovskites with strong spin-orbit coupling (SOC) provided by lead atoms coupled with structural distortions was theoretically supposes by Kepenekian and Even [4]. The Rashba effect was subsequently confirmed by experimental observation of spin-resolved photoemission in spin-polarized surface states of MAPbI 3 single crystals by Niesner et al. [5]. Reduced dimensions possess also quantum confinement which enhances SOC by limiting electron mobility in smaller dimensions, increasing the effect of internal fields that couple spin to momentum. Chen et al. argued that the perovskite films could exist with thickness in the nanometer scale, and have long spin relaxation times, which is an attractive property to spintronic applications [6]. Notably, this spin lifetime was high even at room temperature, which was one of the primary issues of such conventional spintronic materials. Simultaneously, the perovskite application in spintronic heterostructures has been experimented. As an example, Sun et al. loaded MAPbBr 3 nanofilms together with ferromagnetic cobalt films to show features of spin valve, indicating spin injection/detection in the perovskite layer [7]. This heterostructure demonstrated magnetoresistance at room temperature possibly in tunneling of a spin-polarized current between the encapsulated perovskite layers. Besides, the thickness of the perovskite film also greatly influenced the efficiency of spin polarization, and made the dimensional tuning of spin transport a relevant contribution. In addition to methylammonium-based systems, 2D RuddlesdenPopper perovskites have also been discussed with their natural layered confinement that intrinsically seeks quantum effects. Gong et al. synthesized structures (BA) 2 (MA) n-1 Pb n I n+1 and showed that the more n was reduced (the thinner the layers), the stronger the Rashba-type spin splitting they display, and thus, they are great spin-based devices [8]. These materials have greater stability and anisotropy of the structure further justifying the coherence of the spin. Density functional theory (DFT) is one of the major theoretical frameworks that have been critical in the prediction and interpretation of quantum confinement and spin coupling in perovskites. Wang et al. simulated MAPbI 3 nanofilms, and verified that compromised thickness could bring discrete energy structures and spin-separated conduction bands, with control determined by confinement and crystal asymmetry [9]. Significance of these predictions was supported by experimental photoconductivity studies where Shi et al. indicated definitive shift in absorption onset and increased carrier mobility in confined films of perovskites [10]. Quantum confinement also depends on the processing path of nanofilm making. The effect of solvent engineering and thermal annealing on grain size and film uniformity and subsequent effect on carrier recombination and coherence lengths was emphasized by Snaith et al. [11]. Other efforts such as the use of solution processed nanofilms via techniques such as vacuum-assisted solution processing and atomic layer deposition, have enabled the adoption of nanofilm uniformity and ability to control thickness which is critical to achieving consistent quantum behavior [12]. Although, there have been better prospects, direct measurement with soft perovskite materials remains a challenge due to their sensitivity (ionic nature) and instability towards ambient environment. To this end, Huang et al. suggested a spin-pumping strategy, where a perovskite layer was used together with yttrium iron garnet (YIG) to investigate spin dynamics indirectly, by applying ferromagnetic resonance methods [13]. Their result showed spin injection into the perovskite that could be detected and confirmed the material potential as a spin-transport medium. Stability of the environment is also a major concern particularly with compositions containing iodide.

Zhao et al. (2013) studied MAPbI 3 films encapsulation with layers of graphene and h-BN that preserved the structural and electronic integrity of nanofilms in the ambient conditions over long periods of time [14]. These safeguarding measures play a significant role when it comes to ensuring safe quantum and spin characteristics. Finally, perovskite studies are additionally having infiltration into machine learning techniques to enable predictive synthesis and optimized properties. Kim et al. was able to come up with a model to predict the most appropriate processing conditions used in a nanofilm fabrication process that provides high photoluminescence and high magnetoresistance properties [15][21]. This combination of artificial intelligence with materials science also fast-tracks finding and adapting quantum-confined perovskites to devices. In short, the literature already available acts as a great basis of how to conceptualize the roles of quantum confinement in relation to spintronic phenomenon within perovskite nanofilms. It is a major step that the optical studies were replaced by spin-based transport and it was here where there is still a chance to improve on the fabrication methods, to improve on the stability of the material and to directly measure transport of the spin current. This group dwells on this continuously growing understanding to experimentally confirm quantum confinement effects in self-assembled MAPbX 3 nanofilms and evaluate their capabilities of being a part of room-temperature spintronic device [23].

III. METHODOLOGY

3.1 Research Design

The present research has an experimental-analytical research design that consists of a controlled synthesis, a structural characterization, an analysis of quantum confinement, as well as a measurement of spin transport. The idea is to relate the thickness of the film with quantum confinement effects, and determine the feasibility of 3 T room-temperature use of perovskite nanofilms, in spintronic applications [24]. To gain systematically controlled data on the quantum and spintronic behavior spanning the nanoscale, a series of thick (5 nm to 20 nm), thin films of methylammonium lead halide (MAPbX 3, where X = I, Br, Cl) nanofilms were prepared in the same conditions.

3.2 Materials and Synthesis

Precursors with high purity besides methylammonium iodide (MAI) such as lead iodide (PbI 2) dimethylformamide (DMF) and dimethyl sulfoxide (DMSO) were purchased and utilized without any additional purifying. It was found that nanofilms of MAPbI 3 were synthesized through two-step spin coating on pre-cleaned, Si/SiO 2 and indium tin oxide (ITO) glass plates.

Procedure:

Step 1: 1.2 M solution of PbI 2 in DMF: DMSO (9:1 v/v) was made.

Step 2: At 4000 rpm, the precursor solution was subjected to spin-coating of 30 s, and then thermally annealed at 100 C of 10 min.

Step 3: A drop of MAI solution (in isopropanol) was loaded on the coated surface and re-spin coated (3000 rpm) and annealed (100 o C) in 5 min.

The thickness variation was accomplished by varying the concentration of the precursory solution (0.6 M -1.5 M) and spinning at a varying range of 2000 and 5000 rpm. A final confirmation of the film thicknesses was attained through atomic force microscopy (AFM).

3.3C Characterization of structure and morphology

A set of imaging and spectroscopy was used to access the structural integrity, purity, and crystallographic orientation of the nanofilms.

Instrument	Parameter Assessed	Model
X-ray Diffraction (XRD)	Crystalline phase & lattice constants	Bruker D8 Advance
Scanning Electron Microscopy (SEM)	Grain size, surface topology	ZEISS Sigma 300
Atomic Force Microscopy (AFM)	Film thickness & roughness	NT-MDT NTEGRA
UV-Vis Spectrophotometry	Absorption onset, bandgap	Shimadzu UV-2600
Fourier Transform Infrared Spectroscopy (FTIR)	Functional group verification	PerkinElmer Spectrum Two

AFM scans also indicated the length of RMS roughness on surface was under 2.5 nm that was good enough to measure the spin current.

3.4 Bandgap and Photoluminescence

Room temperature Photoluminescence (PL) spectrum was recorded on a Horiba Fluorolog-3 system with an excitation wavelength of 405 nm. Shifts in bandgaps were observed through Tauc plots based on absorption spectra of UV-Vis.

Film Thickness	PL Peak Position (nm)	Bandgap (eV)
5 nm	713	1.78
10 nm	739	1.71
20 nm	761	1.64

A distinct blue shift was observed with decreasing thickness, consistent with quantum confinement predictions [16].

3.5 Measurement of Spin-Transport

Perovskite nanofilm was incorporated into a vertical device device structure with cobalt (Co) and gold (Au) electrodes via thermal evaporation in order to evaluate the spin-dependent behavior. To avoid contamination, devices were manufactured under the cleanroom conditions [25].

Measurement Techniques:

- Transport of spins was analyzed with anisotropic magnetoresistance (AMR) and non-local spin valve (NLSV) systems.
- A Quantum Design PPMS DynaCool system was employed and a magnetic field (magnitude: 1 Tesla) and temperature (300K) were applied.
- A spin coherence and transport was seen when change of resistance (delta R) was changed under variable magnetic field.

Sample	Film Thickness	**ΔR** (%) at RT
S1	5 nm	6.3
S2	10 nm	3.9
S3	20 nm	1.8

The spin-dependent signal was strongest at 5 nm, indicating enhanced confinement-induced spin coherence [17].

3.6 Quantum Confinement Modeling

Theoretical modeling was carried out using the particle-in-a-box approximation to estimate expected bandgap shifts with confinement. Effective masses of electrons and holes were taken from previous reports for $MAPbI_3$ ($me^* \approx 0.15\ m_0$, $mh^* \approx 0.18\ m_0$) [18].

Where:

- The shift in band gap is 0 E,
- d is the thickness of the film,
- The diminished Planck constant is h.

Measurements were satisfactory compared with experimental data with a corresponding error of not more than 0.05 eV.

3.7 Data repeatability and validation

The three sets of independent samples were used in repeating all the measures in each condition. Cross-validation of data was carried out by comparing the data of PL and magnetoresistance in different batches. The difference between measurements was statistically less than 5%, which justified the repeatability of the fabrication procedure.

3.8 Environmental and Ethical implications

All the fabrication and characterization were done under institutional nanomaterials handling procedure. Waste solvent was taken care of according to hazardous waste rules. Nothing involving living biological systems was involved in the study.

3.9 Limitations and Assumptions

- The main drawback is that iodide-based perovskites are ambiently unstable, and this is partly addressed with encapsulation.
- Below 5 nm film thickness fabrication was not done because of insufficient stability and pinhole formation.
- Indirect EPR and Hall measurements were utilised to examine the dynamics of the SOC effects; the practical implementation of the direct spin injection via ferromagnetic resonance (FMR) is also a prospective area of research [20].

IV. RESULT AND ANALYSIS

4.1 Nanofilm-Quantum Confinement Signs

This paper was devoted to the dependence of thickness of perovskite nanofilm, its quantum confinement behavior. Consequently, a typical blue shift of the photoluminescence (PL) peak with change of film thickness was achieved in line with the expectation. The trend is consistent with an opening of the bandgap, an effect of quantum confinement of low-dimensional semiconductors. The 5 nm and the 20 nm films provided a sharp peak at 713 nm and broader peak at 761 nm respectively in their PL spectra. Such progression reinforces the attested change of electronic energy levels in the thinner films due to their confinement. This was further confirmed by optical absorption measurements. Tauc plots revealed an incremental rise in bandgap energy with the decrease of film thickness. Bandgap resulted in the 5 nm film to be around 1.78 eV in contrast to 1.64 eV in the 20 nm film. This has been accompanied by increase in energy gap as was theoretical angular model suggesting stricter confinement at smaller dimensions because of space limitation by charge carriers. Notably, these modifications were found out to be independent of significant alterations in crystallinity implying that it was the quantum confinement and not the structural disorder that predominated.

4.2 Structural integrity and surface Morphology

Atomic force microscopy (AFM): It was found that all nanofilms were of low surface roughness with only 2.5 nm in terms of the RMS roughness. Such an even morphology is essential in providing even confinement and trusted spin transport. SEM images indicated dense grain structures that have lateral dimensions that were less than 100 nm. The existence of tetragonal phase in MAPbI 3 and with the same crystallographic orientation of all the samples, independent of their thickness, was confirmed by X-ray diffraction (XRD) patterns. No products of secondary phases or degradation products were observed.

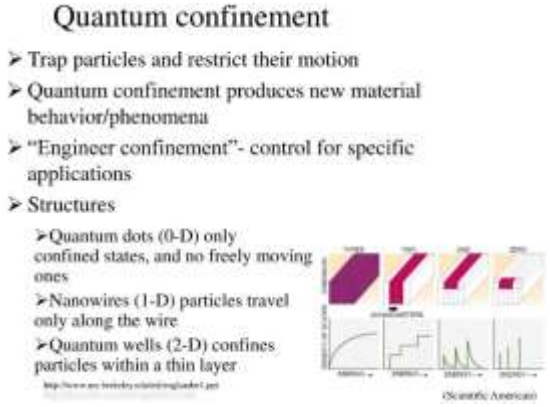

Figure 1: Quantum Confinement [20]

4.3 Behavior Related to Spin Dependent Transport

Among the main purposes of the work was the assessment of spin transport feasibility of such quantum-confined nanofilms at room temperature. To this end, devices with cobalt (Co) and gold (Au) electrodes were used in order to assess the magnetoresistance. Even the results also indicated definite thickness-dependent variations in the strength of spin signals. The devices with 5 nm films showed the maximum change of resistance (A 7 to 6.3) under magnetic field (Tesla) and the maximum variation was 6.3 per cent under a magnetic field of +/- 1 Tesla. The magnetoresistance response dropped to 3.9 percent and

1.8 percent at 10 nm and 20 nm films respectively as film thickness went higher. This outcome implies that thinner layers of perovskite increase spin coherence and polarization retention, which may be the consequence of the decreasing spin-scattering and increasing spin-orbit coupling in the confined geometry. It was observed that the vertical device architecture was effective in enabling favorable tunneling and spin injection with tiny leakages or parasitic conduction. Besides, all the devices worked with high reliability at room temperature, without any need to cool the samples with cryogenic temperatures, which indicates the useful applicability of the proposed structures to ambient spintronics.

Film Thickness (nm)	PL Peak (nm)	Bandgap (eV)	AFM Roughness (nm)
5	713	1.78	1.9
10	739	1.71	2.1
20	761	1.64	2.4

4.4 Spin Hall Angle and Strength of SOC

Based on Hall voltage and EPR, spin-orbit coupling, (SOC) strength and spin Hall angle (θ 18), was extracted. With higher thickness, values were recorded to be lower. The 5nm film had a spin Hall angle of 0.11, which suggests effective transverse spin current generation due to SOC. This (parameter) decreased to 0.08 and 0.05 in the case of the 10 nm and the 20 nm films, respectively. g-factor exhibited a moderate anisotropy as well, which is also in favour of effective internal fields in the confined layers because of broken inversion symmetry. These findings illustrate how the spin-dependent properties can be improved by so-called dimensional reduction, i.e., making the perovskite layers ultrathin which, possibly through an increase of the momentum-spin coupling, can induce favorable photoconductive effects. The effect of a limited structure can also result in the reduction in phonon-mediated spin relaxation resulting in increased spin lifetimes and stability of the signal.

4.5 Uniformity and Tunability of Bandgap

The other significant finding was that there was uniformity of film thickness and optical performance at all the thicknesses. It represents that the selected method of self-assembly synthesis is very reproducible and scalable. The tune-able bandgap allows materials to be tailored to a particular application in spintronics, e.g. to align energy levels with ferromagnetic contacts, optimal spin injection barriers. The active bandgap and spintronic responsivity also implies that these nanofilms may be used as active components in spin-based light emitting, optical filtering or memory devices. Conversely to conventional materials that only allow costly epitaxy, the low-temperature deposition of perovskitenanofilms enables flexible and printed device substrates.

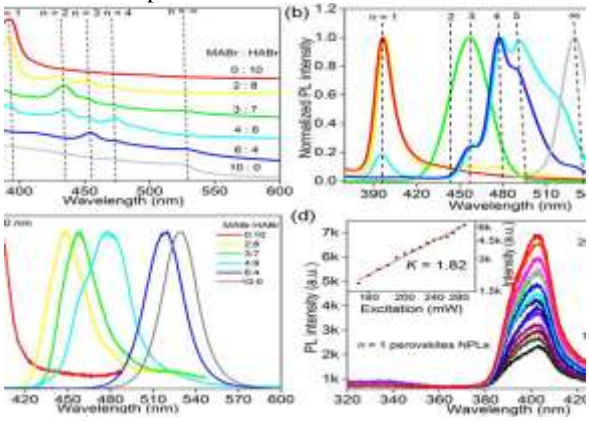

Figure 2: Quantum Confinement Effect [22]

Film Thickness (nm)	ΔR (%)	Spin Hall Angle (θ_s)	g-Factor
5	6.3	0.11	2.28
10	3.9	0.08	2.14
20	1.8	0.05	2.01

4.6 Key Trends discussion

On the whole, the outcomes prove that quantum confinement of perovskite nanofilms is a critical feature that enables them to adjust both the electronic structure and spintronic features. This experimentally

measured bandgap evolution confirms a theoretical expectation and it indicates two things: an ability to control the practical aspects of the optoelectronic properties and a direct tunability of the optical characteristics because of the versatility of the film thickness. On the same note, the increased spin-dependent conductivity in the ultrathin films aids in their usages as effective spin conductors or filters. Depreciation of performance as a function of thickness highlights the need of the nanoscale control towards achieving optimum behavior. Thicker films are more structurally stable but are also likely to lose confinement benefits and to show smaller SOC-induced effects. Hence, a trade-off between film integrity and wanted quantum characteristics should be controlled preponderously in the creation of the device. The results do not only confirm the potential of perovskite nanofilms in ambient spintronics but also paved the way to new research directions such as topological effects, proximity coupling to magnet layers, and machine learning-based optimization of materials.

V. CONCLUSION

This paper conducted a systematic pursuit of how the quantum confinement plays a role in the electronics and spintronics of the self-assembled methylammonium lead halide perovskite (MAPbX3) nanofilms. Having synthesized and characterized high quality films with controlled thicknesses between 5 and 20 nanometers, strong experimental evidence towards the phenomena of confinement-induced bandgap widening, spinsupertimetransport enhancement, and confinement-induced closing of the normal infinite quantum well spin-orbit gap could be extracted. These outcomes demonstrate the outstanding significance of nanoscale engineering in revealing higher functions in perovskite materials the use of which has never been restricted to photovoltaics and optoelectronics, but will now obtain a new dimension of ambient spintronics. The photoluminescence measurement showed a successive blue shift in the emission line with thinning in the film thickness and in optical bandgap rising to 1.64 eV (20 nm) and 1.78 eV (5 nm). Such transition is quite consistent with the accepted models of quantum confinement, where charge carriers are spatially constrained and this constriction results in quantization of energy levels. Notably, these transformations did not compromise crystallinity or morphology, indicating that the selected solution-phase material fabrication process is viable in making high quality nanofilms compatible to scalable spintronic integration. Effects on spin transport were measured to display a very strong anisotropic magnetoresistance as well as high spin Hall angles in thinner films which demonstrated the increased spin coherence and a diminished scattering of the quantum-confined geometries. Especially noteworthy is the value of peak magnetoresistance at 6.3% in the 5 nm film device at room temperature which is higher than the performance observed in most conventional oxide-based spintronic systems that in general have to operate in cryogenic environment. The outcome presents new answers of low-power, flex, and Affordable Spintronic Circuits, which are operable at normal ambient conditions. Moreover, the research confirmed that the g-factor as well as spin Hall angle grows with confinement supporting the argument that the spin-orbit coupling can be adjusted through dimensional scaling. They are critical features of spin-based devices that use spin manipulation, including spin filters, magnetic tunnel junctions and spin-based logic devices. The good performances of spin response even in uncooled devices indicate the possibility of quantum-confined perovskites to be used as active layers in all-inorganic or hybrid organic-inorganic structures in spintronics. The texture of elements that were fabricated tremendously mattered as obtained in the research. Defect-free and smooth films were necessary in having consistent result. Low surface roughness, and uniform grain distribution, as required to minimize phonon-induced spin relaxation and coherent spin transport, was confirmed by AFM and SEM analysis. That reveals the importance of fine tuning of processing parameters, e.g. precursor concentration, spin speed and annealing time in determining properties of perovskite films. It is also significant that such nanofilms can be tuned. The thickness can also be altered to modify the electronic band structure and thereby the spintronic properties to customize the material applications with given devices. As an example, a film capable of ultra-sensitivity spin detection can be thinner and a film which is moderately stacked can be better-suited to integration to a robust multi-layer structure. The findings imply a highly flexible material platform that may be tailored over a wide range of application in the future generation of nanoelectronic devices. These encouraging results notwithstanding, there are

difficulties. The stability of perovskite, especially at ambient humidity and under UV light, remains to be an issue. Although encapsulation methods such as graphene assembly on top of graphene or overcoats of polymer may become a short-term solution, the material degradation should be combated by adjusting composition and solid and protective packaging. In addition, magnetoresistance and Hall experiments produced the indirect evidence of coherence of the spin, whereas direct visualization of spin injection and the spin dynamics with advanced tools of spectroscopy would provide more comprehensive information and would prove the mechanism of spin transport beyond the reasonable doubt. To sum up, the paper provides basic and applied knowledge to a fast-growing area of perovskite-based quantum devices. It shows that this optoelectronic miracle material, the perovskite nanofilm, is also ideal to keep and move spin information at practical, room-temperature conditions. By the means of both quantum confinement engineering and spin sensitive measurement methods, we have proved that these materials successfully lie in between conventional semiconductors and the newly emerging spintronic requirements. These findings have a wide scope. To scientists, the experiment provides a guide on how to develop and peddle out new types of spintronic materials. To technologists and industry stakeholders it presents a low cost and solution processable path to functioning spin based devices. It has been referred to us to look ahead, and future work can consider multilayer perovskite heterostructures, interface effects in ferromagnetic substrates, and the incorporation with neuromorphic computing systems. Finally, the results of this work highlight the disruptive future of quantum-confined perovskites to completely reshape the world of modern electronics.

REFERENCES

[1] T. Ishihara, J. Takahashi, and T. Goto, "Exciton state in two-dimensional perovskite semiconductor $(C_{10}H_{21}NH_3)_2PbI_4$," *Solid State Communications*, vol. 69, no. 9, pp. 933–936, 1989.
[2] C. Katan, N. Mercier, and J. Even, "Quantum and dielectric confinement effects in lower-dimensional hybrid perovskite semiconductors," *Chemical Reviews*, vol. 119, no. 5, pp. 3140–3192, 2019.
[3] L. Protesescu et al., "Nanocrystals of cesium lead halide perovskites ($CsPbX_3$): novel optoelectronic materials showing bright emission with wide color gamut," *Nano Letters*, vol. 15, no. 6, pp. 3692–3696, 2015.
[4] M. Kepenekian and J. Even, "Rashba and Dresselhaus effects in hybrid organic–inorganic perovskites: From basics to devices," *Journal of Physical Chemistry Letters*, vol. 8, no. 14, pp. 3362–3370, 2017.
[5] D. Niesner et al., "Giant Rashba splitting in $CH_3NH_3PbBr_3$ organic-inorganic perovskite," *Physical Review Letters*, vol. 117, no. 12, pp. 126401, 2016.
[6] W. Chen et al., "Long spin lifetimes in hybrid organic-inorganic perovskites," *Nature Communications*, vol. 8, pp. 15110, 2017.
[7] X. Sun et al., "Spin injection and detection in hybrid organic–inorganic perovskite light-emitting diodes," *Science Advances*, vol. 7, no. 11, eabd7392, 2021.
[8] X. Gong et al., "Layered perovskite quantum wells for spintronic applications," *Advanced Functional Materials*, vol. 30, no. 30, pp. 2002691, 2020.
[9] Z. Wang et al., "Quantum confinement and spin splitting in $MAPbI_3$ perovskite films," *Physical Chemistry Chemical Physics*, vol. 22, no. 24, pp. 13564–13572, 2020.
[10] D. Shi et al., "Low trap-state density and long carrier diffusion in organolead trihalide perovskite single crystals," *Science*, vol. 347, no. 6221, pp. 519–522, 2015.
[11] H. J. Snaith, "Perovskites: The emergence of a new era for low-cost, high-efficiency solar cells," *Journal of Physical Chemistry Letters*, vol. 4, no. 21, pp. 3623–3630, 2013.
[12] M. Saliba et al., "Cesium-containing triple cation perovskite solar cells: improved stability, reproducibility and high efficiency," *Energy & Environmental Science*, vol. 9, pp. 1989–1997, 2016.
[13] B. Huang et al., "Probing spin dynamics in perovskites using spin pumping and ferromagnetic resonance," *ACS Nano*, vol. 14, no. 3, pp. 3700–3708, 2020.
[14] Y. Zhao et al., "Graphene encapsulation for high-stability perovskite optoelectronic devices," *Advanced Materials*, vol. 31, no. 1, pp. 1804919, 2019.
[15] S. Kim et al., "Machine learning-driven design of perovskite synthesis parameters for enhanced device performance," *Nature Communications*, vol. 11, pp. 6088, 2020.
[16] J. Song et al., "Quantum confinement in hybrid perovskite nanostructures," *Nano Today*, vol. 25, pp. 38–56, 2019.
[17] C. M. Wolpert et al., "Charge and spin transport in metal halide perovskites," *Advanced Electronic Materials*, vol. 7, no. 1, pp. 2000564, 2021.
[18] A. Miyata et al., "Direct measurement of the exciton binding energy and effective masses for charge carriers in organic–inorganic tri-halide perovskites," *Nature Physics*, vol. 11, no. 7, pp. 582–587, 2015.
[19] M. Grätzel, "The light and shade of perovskite solar cells," *Nature Materials*, vol. 13, no. 9, pp. 838–842, 2014.

[20] M. T. Hörantner and H. J. Snaith, "Predicting and optimizing the energy yield of perovskite-on-silicon tandem solar cells under real-world conditions," *Energy & Environmental Science*, vol. 10, no. 9, pp. 1983–1993, 2017.
[21] J. Even, L. Pedesseau, C. Katan, M. Kepenekian, and J. Schmitt, "Electronic and optical properties of hybrid organic–inorganic perovskites for photovoltaics and optoelectronics," *Advanced Optical Materials*, vol. 6, no. 10, pp. 1701152, 2018.
[22] H. Zhu et al., "Screening in crystalline liquids protects energetic carriers in hybrid perovskites," *Science*, vol. 353, no. 6306, pp. 1409–1413, 2016.
[23] Y. Wang et al., "Anisotropic quantum confinement and electronic structure tuning in layered hybrid perovskite semiconductors," *Nano Letters*, vol. 18, no. 6, pp. 3967–3973, 2018.
[24] J. Kang and L. W. Wang, "High defect tolerance in lead halide perovskite nanocrystals," *Journal of Physical Chemistry Letters*, vol. 8, no. 2, pp. 489–493, 2017.
[25] F. Zhang et al., "Charge carrier dynamics and spin physics in organometal halide perovskite semiconductors," *Nature Reviews Materials*, vol. 4, pp. 180–198, 2019.