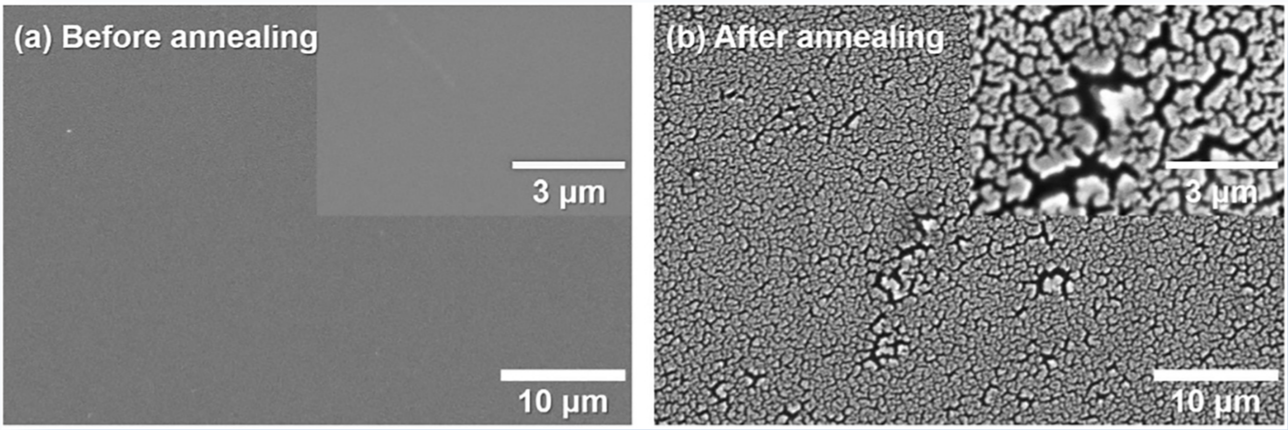

SEM micrographs of CeO_2 thin film deposited for 2.0 h on a Si (100) substrate (a) before and (b) after annealing at 1000 °C for 0.5 h in ambient air.[1]

Annual Report 2021
Photonics Research Laboratory

Prepared by

Nathaniel F. Hermosa, PhD
Program Coordinator
Photonics Research Laboratory
Submitted: January 2022

Contents

[1] *de Mesa, J. A., Rillera, A. P., Empizo, M. J. F., Sarukura, N., Sarmago, R. V., & Garcia, W. O. (2021). Low-energy femtosecond pulsed laser deposition of cerium (IV) oxide thin films on silicon substrates. Journal of Crystal Growth, 574, 126323.*

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1. Executive Summary

1.1. Activities of the research group

1.1.1. Organization

Regular members		3
Student members		
	PhD students	10
	MS students	3
	MSE students	2
	BS students	7
Apprentices		5
Adjunct Researcher		1
Total		31

1.1.2. Mentoring

	Number of graduates
BS Physics	3
BS Applied Physics	5
MS Physics	1
PhD Physics	1
Total	10

1.2. Research highlights

International peer-reviewed journals	4
Local peer-reviewed journals	
International conference papers	
International conference presentations	2
Local conference papers /presentations	10

Chapter in books	
Patents	
NIP funded projects	3
Non-NIP funded projects	2
Major equipment acquired/ upgraded	0
Research travels abroad	0
Visiting researchers	0
MOA's entered with local and foreign institutions	0

1.3. Extension work highlights

Extension work activities	several
Research interns/ OJT's for training held at NIP	0

1.4. Main challenges encountered and proposed solutions

1.5. Awards or accreditations received/ positions of responsibility held and other accomplishments

National awards or accreditation received, positions of responsibility held	0
International awards or accreditations received, positions of responsibility held	0
Other accomplishments	0

2. Technical Report

2.1. Activities of the research group

- The Photonics Research Laboratory continues to hold weekly group meetings. The three clusters of the laboratory also have separate research meetings every week.

- The group published 4 ISI papers.

- The group has participated in international and national Physics conferences. All of these conferences are online.

- The group helped graduate 1 PhD Physics student, 1 MS Physics student, 5 BS Applied Physics students, and 3 BS Physics students.

- Three graduates of the group received awards from the College of Science. Ms. Janelle Manuel and Mr. Roger Jamilarin are recipients of the Leticia Shahani award for most outstanding BS Physics thesis and BS Applied Physics thesis, respectively. Mr. Nathan Suelto is the Most Outstanding BS Physics student.

- Dr. Almoro continues to be a Topical Editor for Applied Optics.

2.1.1. Organizations

2.1.1.1. Group members

Regular members (3)

1. Almoro, Percival
2. Garcia, Wilson
3. Hermosa, Nathaniel II

Adjunct Researcher (1)

1. Dasallas, Lean

Student members (22)

PhD students (10)

1. Abregana, Timothy Joseph (P7)
2. Banguilan, Dina Grace (P3)
3. Binamira, Jonel (P3)
4. Cabanilla, Jayson (P3)
5. De Mesa, Joseph (P6)
6. Emperado, Rommil (P5)
7. Miranda, Jessa Jayne (P4)
8. Olaya, Cherrie May (P5)
9. Onglao, Mario III (P3)
10. Zambale, Niña Angelica (P3)

MS students (3)

1. Pablico, Dennis Angelo (M3)
2. Tabuzo, Rigil (M2)
3. Manuel, Janelle (M1)

MSE students (2)

1. Sagisi, Jenny Lou (P3)
2. De Mata, Joy Kristelle (P2)

BS Applied Physics students (3)

1. Hermosa, Christian Robic (B4)
2. Ambrioso, Benjamin (B4)
3. Grefal, Jess Rudyll (B4)

BS Physics students (7)

1. Valdeavilla, Charlyn (B7)
2. Sarayan, Juan Gabriel (B5)
3. Cabalar, Vincent (B4)
4. Borromeo, John Carlo (B4)

Apprentices (5)

1. Abenojar, Joshua
2. Buensuceso, Cedie
3. Cuadra, Marco
4. Loot, Angela
5. Mullaneda, Jernnex

2.1.1.2. Summary

Regular members			3
Adjunct Researcher			1
Student members			22
	PhD students	10	
	MS students	3	
	MSE students	2	
	BS students	7	
Apprentices			5
		Total	31

2.1.2. Mentoring

2.1.2.1. List of graduates

Mid-year 2019 - 2020 (1 BS)

1. Parales, Ares Amable (Applied Physics)
   Generating and analyzing intensity profiles of cost effective single slits and double slits using a 650nm laser pointer (Adviser: Dr. Wilson Garcia)

1st semester 2020 – 2021 (1 BS, 1 PhD)

1. Lorenzo, Joshua Cesar (Physics)
   Formation and Self-healing of epicycloid and hypocycloid-shaped beams from dynamic curved slits (Adviser: Dr. Nathaniel Hermosa)

2. Simon, Rhenish (PhD)
   Crossing angle measurements as thin film characterization technique (Adviser: Dr. Nathaniel Hermosa)

2nd semester 2020 – 2021 (6 BS, 1 MS)

1. Gloria, Gelli Mae (Applied Physics)
   Model for phase retrieval using partially coherent illumination (Adviser: Dr. Percival Almoro)

2. Jamilarin, Roger (Physics)
   Generation of vortex beams by spiral slit using digital micro mirror device (Adviser: Nathaniel Hermosa)

3. Manuel, Ma. Janelle (Applied Physics)
   Folded transit photometry as an exoplanet detection method (Adviser: Dr. Nathaniel Hermosa)

4. Ofina, Edrien Dominick (Applied Physics)
   Fourier transform profilometry using a smartphone-lens projector setup (Adviser: Dr. Nathaniel Hermosa)

5. Suelto, Nathan (Physics)
   Optimization of initial guess phase for enhanced multiple intensity phase retrieval (Adviser: Dr. Percival Almoro)

6. Tinte, Bienica Yzabelle (Applied Physics)
   Pulsed laser deposition in the 21st century: a review (Adviser: Dr. Wilson Garcia)

7. Revilla, Miguel (MS)
   Detection of exoplanets in face-on orbits using vortex beams and quadrant detection (Adviser: Dr. Nathaniel Hermosa)

2.1.2.2. Summary

	Number of graduates
BS Physics	3
BS Applied Physics	5
MS Physics	1
MS MSE	0
PhD Physics	1
Total	10

2.2. Research highlights

2.2.1. Publication in ISI/SCI and Scopus indexed journals (4)

1. Ferrolino, J. P., Cabello, N. I., De Los Reyes, A., Bardolaza, H., Verona, I. C., Mag-usara, V. K., ... & Estacio, E. (2021). Thickness dependence of the spintronic terahertz emission from Ni/Pt bilayer grown on MgO via electron beam deposition. *Applied Physics Express*, *14*(9), 093001. DOI: https://doi.org/10.35848/1882-0786/ac1b0d

2. de Mesa, J. A., Rillera, A. P., Empizo, M. J. F., Sarukura, N., Sarmago, R. V., & Garcia, W. O. (2021). Low-energy femtosecond pulsed laser deposition of cerium (IV) oxide thin films on silicon substrates. *Journal of Crystal Growth*, *574*, 126323. DOI: https://doi.org/10.1016/j.jcrysgro.2021.126323

3. Olaya, C. M., Hayazawa, N., Balois-Oguchi, M. V., Hermosa, N., & Tanaka, T. (2021). Molecular Monolayer Sensing Using Surface Plasmon Resonance and Angular Goos-Hänchen Shift. *Sensors*, *21*(13), 4593. DOI: **https://doi.org/10.3390/s21134593**

4. Olaya, C. M., Hayazawa, N., Hermosa, N., & Tanaka, T. (2020). Angular Goos–Hänchen Shift Sensor Using a Gold Film Enhanced by Surface Plasmon Resonance. *The Journal of Physical Chemistry A*, *125*(1), 451-458. DOI: https://doi.org/10.1021/acs.jpca.0c09373

2.2.2. Publication in local peer reviewed journals (0)

2.2.3. International conference presentations with full papers

2.2.4. International conference presentations without full papers

1. Hermosa, N., Delos Santos R., Estacio, E. “How to detect Terahertz wave via weak measurement,” The 82nd JSAP Autumn meeting 2021, JSAP-OSA Joint Symposia (On-line) (2021.9.12) (2021).

2. Carlos, E., Laureta, C., and Almoro, P., “Enhanced Detection of Orthodontic Attachment Remnants Using UV Absorption Imaging”, 35th Annual Scientific Meeting IADR-SEA Division, December 9, 2021.

2.2.5. Local conference papers

2.2.5.1. With full paper (10)

1. BJC Ambrosio and NP Hermosa, Orientation of Roman Catholic Churches in the Philippines, *Proceedings of the Samahang Pisika ng Pilipinas* **39**, SPP-2021-PB-21 (2021). URL: https://proceedings.spp-online.org/article/view/SPP-2021-PB-21.

2. DGC Banguilan and NP Hermosa, Vortex beam interaction with a step, *Proceedings of the Samahang Pisika ng Pilipinas* **39**, SPP-2021-2B-04 (2021). URL: https://proceedings.spp-online.org/article/view/SPP-2021-2B-04.

3. CRL Buco and PF Almoro, Accelerated phase aberration compensation using the fast principal component analysis algorithm, *Proceedings of the Samahang Pisika ng Pilipinas* **39**, SPP-2021-3E-04 (2021). URL: https://proceedings.spp-online.org/article/view/SPP-2021-3E-04.

4. RB Emperado, LL Dasallas, and WO Garcia, Demonstration of flip-over effect in laser-produced plasma expansion via Direct Simulation Monte Carlo method, *Proceedings of the Samahang Pisika ng Pilipinas* **39**, SPP-2021-1E-03 (2021). URL: https://proceedings.spp-online.org/article/view/SPP-2021-1E-03.

5. GMP Gloria and PF Almoro, Robustness of phase retrieval under partially coherent illumination, *Proceedings of the Samahang Pisika ng Pilipinas* **39**, SPP-2021-PB-12 (2021). URL: https://proceedings.spp-online.org/article/view/SPP-2021-PB-12.

6. JRB Grefal, RB Emperado, LL Dasallas, and WO Garcia, Effect of off-axis geometry on the thickness profile of film produced by vacuum thermal evaporation, *Proceedings of the Samahang Pisika ng Pilipinas* **39**, SPP-2021-1B-05 (2021). URL: https://proceedings.spp-online.org/article/view/SPP-2021-1B-05.

7. JP Ferrolino, NI Cabello, A De Los Reyes, H Bardolaza, IC Verona, VK Mag-usara, J Afalla, M Talara, H Kitahara, W Garcia, A Somintac, A Salvador, M Tani, and E Estacio, Ni/Pt spintronic emitters as potential reliable THz source, *Proceedings of the Samahang Pisika ng Pilipinas* **39**, SPP-2021-3E-02 (2021). URL: https://proceedings.spp-online.org/article/view/SPP-2021-3E-02.

8. MJS Onglao and PF Almoro, Numerical investigation on the size of speckle produced by phase modulation at the Fourier plane, *Proceedings of the Samahang Pisika ng Pilipinas* **39**, SPP-2021-PB-11 (2021). URL: https://proceedings.spp-online.org/article/view/SPP-2021-PB-11.

9. JLB Sagisi, WO Garcia, and LL Dasallas, Biburst pulses as temporal laser source term for pulsed laser ablation of metals, *Proceedings of the Samahang Pisika ng Pilipinas* **39**, SPP-2021-1E-02 (2021). URL: https://proceedings.spp-online.org/article/view/SPP-2021-1E-02.

10. NC Suelto and P Almoro, Optimization of initial guess phase for multiple intensity phase retrieval, *Proceedings of the Samahang Pisika ng Pilipinas* **39**, SPP-2021-PB-08 (2021). URL: https://proceedings.spp-online.org/article/view/SPP-2021-PB-08.

2.2.6. Chapters in books (0)

2.2.7. Patents (0)

2.2.8. NIP funded projects (3)

Project proponent	Project title	Period	Amount	Project grantor
Almoro, Percival	Enhanced phase retrieval using wavelength-distance transformation and unordered propagations	01 January 2021 – 31 December 2021	PhP 105,600.00	NIP/ UP Diliman
Garcia, Wilson	Experimental and Computer Modeling of Laser Ablation	01 January 2021 – 31 December 2021	PhP 105,600.00	NIP/ UP Diliman
Hermosa, Nathaniel	Goos-Hänchen shift from frustrated Total Interntal Reflection	01 January 2021 – 31 December 2021	PhP 105,600.00	NIP/ UP Diliman

2.2.9. Non-NIP funded projects (2)

Project proponent	Project title	Period	Amount	Project grantor
Hermosa, Nathaniel	Fast Rotation and Translation Sensing with Spatial Mode Projection	01 July 2020 – 31 December 2021	PhP 600,000.00	UP System
Dasallas, Lean	Investigation of material surface modification made by femtosecond pulsed laser ablation from multiple pulses.	July 2020 to December 2021	PhP 500,000.00	UP System

2.2.10. Major equipment acquired (0)
2.2.11. Research travels abroad (0)
2.2.12. Visiting researchers (0)
2.2.13. MOA’s entered with local or foreign institutions (0)

2.3. Extension work highlights

2.3.1. Extension work activities (20)

Abregana, Timothy Joseph	Reviewer, 39th Samahang Pisika ng Pilipinas Physics Congress
Almoro, Percival	NRCP Webinar Resource Person, “Lights Applications and Safety: Pagbibilad , Pagbibilad sa UV”, July 29, 2021 NAST Webinar Resource Person “Scientific Group Mentoring and Online Research Apprenticeship” 13 December 2021 Topical Editor, Optics and Image Processing, 39th Samahang Pisika ng Pilipinas Physics Congress Topical Editor, Applied Optics Reviewer, Optics Letters, Applied Optics
Banguilan, Dina Grace	Reviewer, 39th Samahang Pisika ng Pilipinas Physics Congress Reviewer, OSA Journals
Binamira, Jonel	Reviewer, 39th Samahang Pisika ng Pilipinas Physics Congress
Cabanilla, Jayson	Reviewer, 39th Samahang Pisika ng Pilipinas Physics Congress
Dasallas, Lean	Topical Editor, Photonics and Materials Physics, 39th Samahang Pisika ng Pilipinas Physics Congress
De Mesa, Joseph	Reviewer, 39th Samahang Pisika ng Pilipinas Physics Congress
Emperado, Rommil	Reviewer, 39th Samahang Pisika ng Pilipinas Physics Congress
Hermosa, Nathaniel	Topical Editor, Photonics and Optics, 39th Samahang Pisika ng Pilipinas Physics Congress Reviewer, OSA Journals,IEEE Photonics Journal, Journal of

	Applied Physics D, Applied Physics B, Scientific Reports, Results in Optics, Results in Physics, Journal of Optics
Miranda, Jayne	Reviewer, 39th Samahang Pisika ng Pilipinas Physics Congress
Onglao, Mario	Reviewer, 39th Samahang Pisika ng Pilipinas Physics Congress
Sagisi, Jenny Lou	Reviewer, 39th Samahang Pisika ng Pilipinas Physics Congress
Zambale, Nina Angelica	Reviewer, 39th Samahang Pisika ng Pilipinas Physics Congress

2.3.2. Research interns/OJT's (0)

2.4. Main challenges encountered and proposed solutions

Due to problems related to the pandemic, some students struggle to participate in research meetings. It is suggested that adjustments in the research activities and targets be made iteratively.

2.5. Awards or accreditations received/ positions of responsibility held and other accomplishments (3)

1. Roger Jamilarin, Most Outstanding BS Applied Physics Thesis awardee (SY 2020 – 2021)
2. Janelle Manuel, Most Outstanding BS Physics Thesis awardee (SY 2020 – 2021)
3. Nathan Suelto, Most Ouststanding BS Physics graduate (SY 2020-2021)

3. **Photos, ISI/SCI Publications and other appendices**

3.1. Photos

3.2. ISI/SCI Publications

Applied Physics Express 14, 093001 (2021) LETTER
https://doi.org/10.35848/1882-0786/ac1b0d

Thickness dependence of the spintronic terahertz emission from Ni/Pt bilayer grown on MgO via electron beam deposition

John Paul Ferrolino[1*], Neil Irvin Cabello[2], Alexander De Los Reyes[2], Hannah Bardolaza[2], Ivan Cedrick Verona[2], Valynn Katrine Mag-usara[3], Jessica Pauline Afalla[3], Miezel Talara[3], Hideaki Kitahara[3], Wilson Garcia[2], Armando Somintac[2], Arnel Salvador[2], Masahiko Tani[3], and Elmer Estacio[2]

[1]Material Science and Engineering Program, University of the Philippines Diliman, Quezon City, 1101 Philippines
[2]National Institute of Physics, University of the Philippines Diliman, Quezon City, 1101 Philippines
[3]Research Center for Development of Far Infrared Region, University of Fukui, Bunkyo 3-9-1, Fukui City 910-8507, Japan

[*]E-mail: jrferrolino@msep.upd.edu.ph

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We report on the spintronic terahertz (THz) emission from a Ni/Pt bilayer on MgO grown via electron beam deposition. The films were grown with varying Ni thicknesses with a constant Pt thickness. The nominal Ni thickness values of 3, 5, 7, 9, 15, and 23 nm exhibited thickness-dependence of the THz emission intensities which was well-fitted with a model by Torosyan et al. Thickness-dependence was also observed for the peak frequencies and bandwidth characteristics. These results are consistent with previously reported MBE-grown ferromagnetic/nonmagnetic metal spintronic THz emitters utilizing the inverse spin-Hall effect.

Metallic spintronic terahertz (THz) emitters have gained considerable interest since being reported by Kampfrath et al. in 2013.[1–6] The basic design consists of a bilayer of few nanometer-thick ferromagnetic (FM) and nonmagnetic metal (NM) metal heterostructure. This FM/NM structure generates THz radiation due to the spin-to-charge conversion by the inverse spin-Hall effect (ISHE),[1–3] which governs systems with strong spin–orbit coupling.[7] The THz emission via ISHE is described in Fig. 1. The advantages of this emitter lie in its ease of sample fabrication, as it requires no lithographic procedures; its sample robustness; and its ability to be used without an external voltage bias[4,5] and minimal optical alignment.[3–5] The emitter also generates wide bandwidth THz emission and independent of the wavelength of the pump laser for energy absorption.[2,5]

To optimize the FM/NM metal emitters, the thickness of the metal layers has been examined. Seifert et al. introduced a model for the effect of the total metal thickness on the generated THz radiation intensity.[2] The model was then improved by Torosyan et al., considering the individual thickness of the FM and NM layers.[4] Aside from the thickness, the THz radiation from different FM (such as Ni, Co, Fe) and NM (such as Pt, W, Ta) layers have also been investigated.[2,3,10] For the NM material, Pt delivered the highest THz output compared with other materials. This is attributed to its large spin-Hall angle, γ:[2,10] a requirement for ISHE. In conjunction with Pt, the choice of FM material was found to have relatively little effect; except for Ni, which yielded less than 20% of the maximum THz output.[11] As a result, Ni remains unpopular while other FM materials, such Fe[4,5] and Co,[12,13] have been used in different studies on THz spintronics.

In this work, the terahertz emission from Ni/Pt bilayer was investigated by varying the Ni thickness, d_{Ni}, while keeping Pt constant. The Ni and Pt metal layers were grown on MgO via electron beam deposition as it deposits a more homogenous film surface compared to a sputtering system[14] and is more cost-effective than MBE albeit at a slightly lower crystal quality and film purity.[14,15] The theoretical model, which considers the pump beam absorption at different metal layer thickness,[4] is used to explain the experimental results.

Ni and Pt were deposited on MgO substrates via electron beam deposition at a base pressure of 4.5×10^{-4} Pa. The deposition rate is at ~0.4–0.6 Å s^{-1} measured by a calibrated 5 MHz quartz crystal oscillator. The pellets used have a purity of 4 N from Kurt J. Lesker. Different samples were grown with varying d_{Ni} with estimated values of 3 ± 1 nm, 5 ± 1 nm, 7 ± 1 nm, 9 ± 1 nm, 15 ± 1 nm, and 23 ± 1 nm. The thickness of Pt, d_{Pt}, is set to constant at 6 ± 1 nm which is chosen close to the thickness used in Ref. 3.

The presence of Ni and Pt were confirmed via an elemental analysis using energy-dispersive X-ray (EDX) in conjunction with a scanning electron microscopy. Figure 2 shows peaks of the present elements. Intense peaks associated with Mg and O are also present, which correspond to the substrate. The carbon peak originates from the carbon tape used as adhesive for the samples during the measurement.

A standard THz time-domain spectroscopy (THz-TDS) setup in transmission geometry was employed in obtaining the THz emission spectra from the Ni/Pt on MgO sample. A Menlo femtosecond (fs) fiber laser source was used as the excitation source, which emits 100 fs pulses at a central wavelength, λ, of 780 nm and repetition rate of ~100 MHz. The laser beam is split into pump and probe beams by a beam splitter. The pump beam was mechanically chopped by an optical chopper set at a frequency of 2 kHz. An aspheric lens (f = 7.5 mm) was used to focus the laser beam on the metal side of the sample creating a spot size of ~7.5 μm. The average pump power measured after the optical chopper is ~55 mW. The calculated pump fluence, F, is ~2.5 mJ cm^{-2}. Based on the results of Ref. 4, saturation of the THz emission can be observed at values higher than 5 mJ cm^{-2}. A transverse magnetic field strength of 20 mT was applied parallel to the sample surface using permanent magnets. The flat side of the hyper-hemispherical Si lens was attached directly at the back of the sample (MgO side) to collimate the THz emission. This emission was detected by an LT-GaAs dipole photoconductive antenna (PCA) gated by the probe beam at ~20 mW.

Initially, electrical resistance measurements for varying probe separation distances were performed to assess the metal quality in terms of the thickness and lateral isotropy of the samples. Six different spots were sampled and the results were tabulated in Table I. Increasing d_{Ni} should decrease the electrical resistance of Ni, R_{Ni}, since electrons can move with

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journal homepage: www.elsevier.com/locate/jcrysgro

Low-energy femtosecond pulsed laser deposition of cerium (IV) oxide thin films on silicon substrates

Joseph A. De Mesa [a,*], Angelo P. Rillera [a], Melvin John F. Empizo [b], Nobuhiko Sarukura [b], Roland V. Sarmago [a], Wilson O. Garcia [a,b]

[a] National Institute of Physics, University of the Philippines Diliman, Diliman, Quezon City 1101, Philippines
[b] Institute of Laser Engineering, 2-6 Yamadaoka, Suita, Osaka 565-0871, Japan

ARTICLE INFO

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Keywords:
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A1. Crystal structure
A1. Surfaces
A3. Pulsed laser deposition
B1. Oxides
B1. Rare earth compounds

ABSTRACT

Cerium (IV) oxide (CeO_2, ceria, or cerium dioxide) has been investigated for various applications due to its excellent physical and chemical properties. Since high-precision processing of such functional material can be conceived through pulsed laser deposition (PLD) with a low-energy, ultrashort pulsed laser, we report the low-energy (~ 8.0 nJ) femtosecond PLD (fs-PLD) of CeO_2 thin films on silicon (Si) substrates. The CeO_2 thin films are deposited for 2.0 to 5.0 h at room temperature with background oxygen (O_2) gas and then annealed at 1000 °C for 0.5 h in ambient air. The as-deposited CeO_2 film is amorphous and featureless due to the low-energy laser pulse and room-temperature deposition but exhibits good stoichiometry due to the background gas. The film properties likewise improve with post-deposition annealing coupled with a longer deposition time. Despite the change in stoichiometry, the annealed CeO_2 films exhibit improved reflectivity and enhanced crystallinity. Although other deposition parameters need to be optimized further and the film stoichiometry entails additional examination, our results show the viability of low-energy fs-PLD for the fabrication of CeO_2 thin films and similar functional materials.

1. Introduction

Cerium (IV) oxide (CeO_2), also known as ceria or cerium dioxide, is one of the most abundant and stable rare earth metal oxides found in the earth's crust. As a functional material, CeO_2 exhibits desirable properties such as wide bandgap (3.6 ~ 6 eV), high refractive index ($n = 2$ at 500 nm), high visible to near-infrared transparency, high melting point (2873 K), thermal stability, and good adhesion. Due to these properties, different forms of CeO_2 have been investigated for various applications. For example, CeO_2 nanoparticles on carbon cloth have been shown to exhibit high energy storage performance that is attributed to the rich redox chemistry and porous structure of CeO_2 [1]. CeO_2 nanoparticles have also been synthesized by laser ablation in water, and their antibacterial activity and minimal inhibition concentration have been examined [2]. On the other hand, CeO_2 thin films have been used as buffer layers for the preparation of superconducting $YBa_2Cu_3O_7$ (YBCO) films through chemical solution-based coating pyrolysis [3]. In addition, with CeO_2's high dielectric constant of up to 26 and Ce ions' variable valence states of Ce^{3+} and Ce^{4+}, CeO_2 films have been fabricated as gate dielectrics of metal–oxide semiconductor field-effect transistors (MOSFETs) and capacitors [4,5].

Given their numerous applications, CeO_2 thin films have been deposited on a variety of substrates through chemical vapor deposition (CVD) [6], electron beam evaporation [7], sputtering [8,9], molecular beam epitaxy (MBE) [10], atomic layer deposition (ALD) [11,12], and pulsed laser deposition (PLD) [13–18]. Among these techniques, PLD is considered suitable in fabricating high-quality metal oxide films due to the improvement of the layer-by-layer growth, the control of film surface morphology and stoichiometry, and the possible deposition at relatively low temperatures [18–20]. In depositing a material on a desired substrate, PLD utilizes a pulsed laser beam to ablate the target material either through vaporization, melting, or direct particle ejection, and the deposition involves four stages namely: (1) laser-target interaction, (2) plasma plume generation and expansion, (3) plasma plume-substrate interaction, and (4) film nucleation and growth [21]. The first two stages are complex phenomena wherein the complexity originates from the dependence of laser ablation and plume expansion on the laser characteristics and ambient deposition conditions

* Corresponding author.
E-mail address: jdemesa@nip.upd.edu.ph (J.A. De Mesa).

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Available online 1 September 2021

THE JOURNAL OF PHYSICAL CHEMISTRY A

pubs.acs.org/JPCA Article

Angular Goos–Hänchen Shift Sensor Using a Gold Film Enhanced by Surface Plasmon Resonance

Cherrie May Olaya, Norihiko Hayazawa, Nathaniel Hermosa, and Takuo Tanaka*

Cite This: J. Phys. Chem. A 2021, 125, 451–458 Read Online

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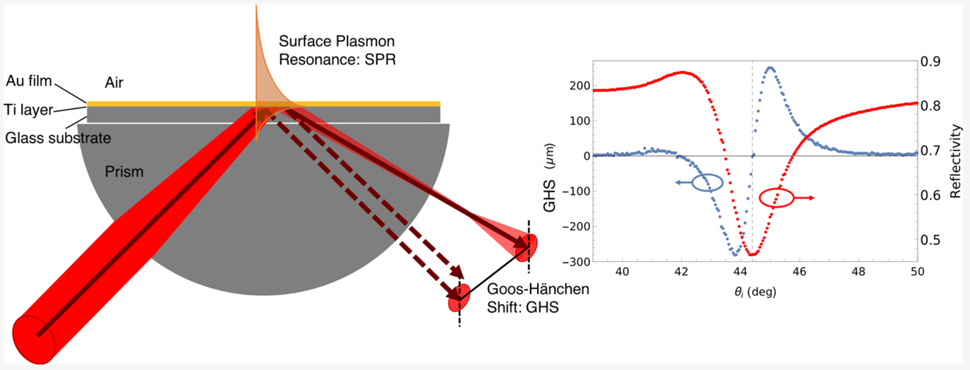

ABSTRACT: We demonstrate the surface plasmon resonance (SPR)-enhanced angular Goos–Hänchen (GH) shift. Typical SPR-enhanced GH shift measurements make use of loosely collimated beams, which enhances only the spatial GH shift (Δ_{GH}). Unlike this scheme, we focused the incident beam to a small beam waist to induce enhancement in the angular GH shift (Θ_{GH}). Although this makes Δ_{GH} negligible, the enhancement of Θ_{GH} is much larger than the decrease in Δ_{GH}. In order to excite surface plasmons, we employ a Kretschmann configuration using a simple gold (Au) film on a substrate. We show that although the efficiency of surface plasmon excitation is decreased by the focused geometry, a significantly large Θ_{GH} was induced. With the simultaneous measurement of reflectivity for SPR and the beam shift for the GH shift used in this work, we experimentally show the potential of measuring enhanced Θ_{GH} toward sensing application when the Au film is exposed to local environmental changes even in the simplest thin film structure.

INTRODUCTION

The Goos–Hänchen (GH) shift is the lateral displacement of an optical beam upon interaction with a planar surface.[1] Using the stationary-phase method, Artmann formulated that the GH shift is proportional to the angular derivative of the phase of the complex reflectivity.[2] Components of wave vectors of optical beams undergo different phase changes upon reflection. When these wave vectors are recombined, their components induce a so-called spatial GH shift (Δ_{GH}), in which the beam is laterally displaced with respect to the prediction of geometric optics.[2−4] This formulation has been widely used when studying the GH shift of different kinds of materials. There is, however, a lesser known related effect, which occurs under partial reflection where wave vector components of the reflected beam also undergo an amplitude change. The reflected beam becomes distorted after reflection, leading to a propagation-dependent deflection manifested as a shift in the tilt of the reflected beam, which is termed the angular Goos–Hänchen shift (Θ_{GH}).[5−7] Θ_{GH} is proportional to the angular derivative of the amplitude of the complex reflectivity.[8] More detailed derivation by Bliokh et al.[1] showed that the Δ_{GH} described by Artmann and the Θ_{GH} are both consequences of the diffractive correction to the reflection coefficient when real optical beams interact with a planar surface. The magnitude of the GH shift observed in experiments is the shift of the beam spot in space at the detector, which includes the Δ_{GH} and the corresponding beam shift induced by Θ_{GH}. Typically, the total shift is comparable to the wavelength of the incident source. Thus, for any practical purposes, enhancement of the shift is necessary. This enhancement could be induced by large modulation in the complex amplitude of the reflected field such as when the incident angle is near the critical angle during total internal reflection (TIR)[9−11] or during excitation of surface modes.[12−15] In particular, studies on the measurement of the enhanced GH shift at surface plasmon resonance (SPR) have been increasing owing to its potential sensing

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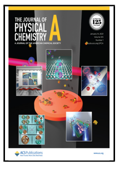

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Molecular Monolayer Sensing Using Surface Plasmon Resonance and Angular Goos-Hänchen Shift

Cherrie May Olaya [1,2], Norihiko Hayazawa [1,2], Maria Vanessa Balois-Oguchi [2], Nathaniel Hermosa [1] and Takuo Tanaka [1,2,3,*]

1 National Institute of Physics, University of the Philippines Diliman, Quezon City 1101, Philippines; cherriemay.olaya@riken.jp (C.M.O.); hayazawa@riken.jp (N.H.); nhermosa@nip.upd.edu.ph (N.H.)
2 Innovative Photon Manipulation Research Team, RIKEN Center for Advanced Photonics, Wako 351-0198, Japan; mariavanessa.balois@riken.jp
3 Metamaterials Laboratory, RIKEN Cluster for Pioneering Research, Wako 351-0198, Japan
* Correspondence: t-tanaka@riken.jp

Abstract: We demonstrate potential molecular monolayer detection using measurements of surface plasmon resonance (SPR) and angular Goos-Hänchen (GH) shift. Here, the molecular monolayer of interest is a benzenethiol self-assembled monolayer (BT-SAM) adsorbed on a gold (Au) substrate. Excitation of surface plasmons enhanced the GH shift which was dominated by angular GH shift because we focused the incident beam to a small beam waist making spatial GH shift negligible. For measurements in ambient, the presence of BT-SAM on a Au substrate induces hydrophobicity which decreases the likelihood of contamination on the surface allowing for molecular monolayer sensing. This is in contrast to the hydrophilic nature of a clean Au surface that is highly susceptible to contamination. Since our measurements were made in ambient, larger SPR angle than the expected value was measured due to the contamination in the Au substrate. In contrast, the SPR angle was smaller when BT-SAM coated the Au substrate due to the minimization of contaminants brought about by Au surface modification. Detection of the molecular monolayer acounts for the small change in the SPR angle from the expected value.

Keywords: surface plasmon resonance; goos-hänchen shift; fresnel; plasmon; self-assembled monolayer

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1. Introduction

Goos-Hänchen (GH) shift is a diffractive correction to the reflection coefficient that results from the interaction of an optical beam and a planar interface [1]. The components of the wave vector undergo different phase and amplitude changes after reflection. When these wave vector components recombine, a lateral shift and a tilt are induced in the reflected beam with respect to the values predicted by geometric optics [2–4]. The lateral shift, which is also called spatial GH (Δ_{GH}) shift, results from the phase changes in the wave vector components. Based on the stationary phase method, Artmann's formulation showed that Δ_{GH} is proportional to the angular derivative of the phase of the complex reflectivity [2]. The tilt in the reflected beam, termed angular GH (Θ_{GH}) shift, results from the amplitude changes in the wave vector components. The change in the amplitude leads to a distortion of the reflected beam inducing a propagation-dependent deflection [5–7]. Θ_{GH} is proportional to the angular derivative of the amplitude of complex reflectivity [8]. The reflected beam, then, experiences a total GH shift that is the linear combination of Δ_{GH} and Θ_{GH} [9]. Typically, GH shift is of the same order of magnitude as the incident source. As such, enhancement is necessary for any practical sensing purposes. Excitation of surface plasmons is one way of enhancing the GH shift, and GH shift measurement at surface plasmon resonance (SPR) has been shown to have great potential in high sensitivity refractive index (RI) sensing [10–13].