Sumanshu Agarwal (PhD IIT Bombay)

Department of Electronics and Communication Engineering,
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EXPERIENCE

Feb 2018–Present **Associate Professor,** *Department of Electronics and Communication Engineering, Institute of Technical Education and Research, Siksha 'O' Anusandhan Deemed to be University*

- Taught 11 courses ranging from basic physics (mechanics) to analog filter design to electromagnetic waves propagation
- Contributed to 5 published journal articles and presented the work at several conferences.
- Coordinated 3 courses
- Organized hands on workshop on Python for ITER students and research scholars

Sep 2017–Jan 2018 **Assistant Professor,** *Department of Electronics and Communication Engineering, Institute of Technical Education and Research, Siksha 'O' Anusandhan Deemed to be University*

- Taught 2 courses
- Subject development committee member of Optical Fiber Communication

Jun 2017–Aug 2017 **Research Associate,** *Department of Energy Science and Engineering, Indian Institute of Technology Bombay*

- Contributed to 1 journal article

Aug 2014–May 2017 **Lab Admin,** *Laboratory for Computation in Nanoelectronics, Department of Electrical Engineering, Indian Institute of Technology Bombay* (Lab in-charge: Prof. Pradeep R. Nair)

- Set up and maintenance of the server system having COMSOL and MatLab to be used (remotely using ssh protocol) by 6 research scholars and 5 M.Tech. students then (and many more have benefitted by now) by using CentOS.
- Resolved or arranged the help for the bugs in the operating systems/hardware in the lab computers

Jul 2011–Jul 2016 **Teaching Assistantship,** *Department of Energy Science and Engineering, Indian Institute of Technology Bombay*

- Assisted the faculties in Solar Photovoltaic, Fundamentals, Technologies and Applications, Mathematical Foundation of Energy Science, and Computational Laboratory courses.
- Coordinator, Venue management for 3rd International Conference on Advances in Energy Research

EDUCATION

Jan 2011 - Nov 2017 Indian Institute of Technology, Bombay, India
Ph.D., Energy Science and Engineering
Dissertation Topic: *Device Physics and Performance Optimization of Perovskite Solar Cells*
Advisors: *Prof. Shaibal K. Sarkar and Prof. Pradeep R. Nair*

Jul 2009 - Dec 2011 Indian Institute of Technology, Bombay, India
MSc., Energy Science and Engineering
Dissertation Topic*: Modeling of Dye Sensitized Solar Cells*
Advisors: *Prof. Shaibal K. Sarkar and Prof. Santanu Bandyopadhyay*
CPI: 8.7/10

https://publons.com/researcher/1440045/dr-sumanshu-agarwal **ORCiD:** 0000-0002-3403-1409

Jul 2006 - May 2009 Maharshi Dayanand University, Rohtak, India
B.Sc., Physics, Chemistry, and Mathematics
Percentage: 79.8%

2006 Board of School Education Haryana, India
Senior Secondary, English, Hindi, Physics, Chemistry, and Mathematics
GPA: 8.8/10

2004 Board of School Education Haryana, India
Matriculation, English, Hindi, Sanskrit, Mathematics, Science, and Social Studies
Percentage: 81.3%

RESEARCH INTERESTS

Thin Film Solar cells, Chalcogenide based solar cells, Solar panel reliability, Energy system modeling, Semiconductor device physics, Optical modeling, Thin film devices, Device interface modeling

SKILLS

Computational: Sentaurus, Silvaco, Comsol Wave Optics Module, SCAPS, NI Multisim, AFORS-HET, Abinit, PC1D, Spice, MatLab, Python, etc.

Analytical: Numerical analysis, Finite-difference discretization, Loss analysis, Physics-based modelling, Process Integration and Pinch Analysis, Energy auditing, etc.

Tools Developed: Solar Photovoltaics SQ Limit Calculator (using MatLab), Photocurrent Analyzer for Solar Cells (MatLab and Excel)

SUPERVISION

- Supervised 5 senior design projects (B.Tech.) at ITER
- Supervising 1 PhD scholar at ITER.

COURSES TAUGHT AT ITER

- ***Analog Filter Design (Theory and Lab)*** (Coordinator)
- University Physics: Electricity and Magnetism (Theory and Lab)
- University Physics: Mechanics (Theory and Lab)
- Electromagnetic Waves-I
- ***Electromagnetic Waves-II*** (Coordinator)
- Optics and Quantum Physics (Lab)
- ***Optical Fiber Communication*** (Subject Development Committee Member)
- Numerical Methods (Theory and Lab)
- ***The Technical Writing Process*** (Coordinator)
- Digital Filter Design (Lab)
- ***Fundamentals of Solar Cells*** (Developed)
- Linear Integrated Circuits

SCHOLASTIC ACHIEVEMENTS

- **10 published (SCI)** and a few under preparation journal articles.
- **Research paper was highlighted on the homepage of IIT Bombay website** in July 2015 <http://www.iitb.ac.in/en/research-highlight/physics-behind-perovskite>
- **Best oral presentation award**, National Symposium for Material Research Scholars, MR-15, IIT Bombay, India
- Class **topper in M.Sc.**
- College **topper in B.Sc.**
- Placed in top 4% out of 73122 candidates in 5th NIIT national IT aptitude test (2009).

 ORCiD: 0000-0002-3403-1409

- Overall distinction in **Senior Secondary (10+2)** and **Matriculation (10)** Examinations.

PUBLICATION

Journals (* denotes the publication as corresponding author)

[J1]. Vikas Nandal, **Sumanshu Agarwal***, Pradeep R. Nair; Deciphering capacitance frequency technique for performance limiting defect state parameters in energy harvesting perovskites, *Physical Chemistry and Chemical Physics*, 2021 23 (42), 24421

[J2]. Kundan Kumar and **Sumanshu Agarwal**, Optimal residual subspace model for structural damage diagnosis: An approach independent of operational and environmental variations, *Int. J. of Structural Engineering*, 2022 12 (1), 44

[J3]. **Sumanshu Agarwal***, Vikas Nandal, Harekrishna Yadav, and Kundan Kumar; Antimony chalcogenide-based Thin Film Solar Cells: Device Engineering Routes to Boost the Performance, *Journal of Applied Physics*, 2021 129 (20), 203101

[J4]. Arun Agarwal, Gourav Misra, **Sumanshu Agarwal**, Kuntal Ghosh; 5G Wireless Cellular Networks: A Conceptual Analysis on Perception, Network Requirements and Enabling Technologies, *Journal of The Institution of Engineers (India): Series B*, 2019 100 (2), 187-191

[J5]. **Sumanshu Agarwal*** and Pradeep R. Nair; Performance Loss Analysis and Design Space Optimization of Perovskite Solar Cells, *Journal of Applied Physics*, 2018 124 (18), 183101

[J6]. Garima Agarwal, Chandan Das, **Sumanshu Agarwal**, Sandeep K. Maurya, Pradeep R. Nair, and Balasubramaniam Kavaipatti; Hall Mobility of as-Grown Cu_2O Thin Films Obtained via Electrodeposition on Patterned Au Substrates, *Physica Status Solidi- Rapid Research Letter*, **2017** 12 (1), 170312

[J7]. **Sumanshu Agarwal*** and Pradeep R. Nair; Pinhole Induced Efficiency Variation in Perovskite Solar Cells, *Journal of Applied Physics*, **2017** 122 (16), 163104

[J8]. Anand S. Subbiah, Neha Mahuli, **Sumanshu Agarwal**, Maikel van Hest, and Shaibal K. Sarkar; Towards All Inorganic Transport Layers for Wide-Band Gap FAPbBr3 based Planar Photovoltaics, *Energy Technology*, 2017 5 (10), 1800

[J9]. Minu Mohan, Vikas Nandal, Sanish Paramadam, Kasala Prabhakar Reddy, Sekar Ramkumar, **Sumanshu Agarwal**, Chinnakonda S. Gopinath, Pradeep R. Nair, and Manoj A. G. Namboothiry; Efficient Organic Photovoltaics with Improved Charge Extraction and High Short-Circuit Current, *The Journal of Physical Chemistry C*, 2017 121 (10), 5523-5530

[J10]. Anand S. Subbiah, **Sumanshu Agarwal**, Neha Mahuli, Pradeep R. Nair, Maikel van Hest, and Shaibal K. Sarkar; Stable p-i-n $FAPbBr_3$ Devices with Improved Efficiency using Sputtered ZnO as Electron Transport Layer, *Advanced Materials Interfaces* **2017** 4 (8), 1601143

[J11]. **Sumanshu Agarwal*** and Pradeep R. Nair; Device Engineering of Perovskite Solar Cells to Achieve Near Ideal Efficiency; *Applied Physics Letters*, **2015** 107 (12), 123901

[J12]. **Sumanshu Agarwal***, Madhu Seetharaman, Naresh K. Kumawat, Anand S. Subbiah, Shaibal K. Sarkar, Dinesh Kabra, Manoj A. G. Namboothiry, Pradeep R. Nair; On the Uniqueness of Ideality Factor and Voltage Exponent of Perovskite-Based Solar Cells; *Journal of Physical Chemistry Letters*, **2014** 5 (23), 4115-4121

Conferences (with proceedings)

[C1]. **Sumanshu Agarwal***, Archana Kumari Munda, Vedika Pandey; Performance Evaluation of Perovskite Solar Cells at Elevated Temperatures, 3rd International Conference on Communication, Circuits and Systems (IC3S), **2020** Bhubaneswar, India.

[C2]. Debojyoti Mallick, Kundan Kumar, **Sumanshu Agarwal**; Blood Vessel Detection Using Modified Multiscale MF-FDOG Filters for Diabetic Retinopathy, International Conference on Applied Machine Learning (ICAML), **2019**, Bhubaneswar, India.

[C3]. **Sumanshu Agarwal***, Arun Agarwal, and Kabita Agarwal; First-Order Calculation of Performance Metrics of Perovskite/Si Tandem Solar Cells, International conference on Trends in Material Science and Inventive Materials, **Mar 2019**, Tamil Nadu, India.

[C4]. Gourav Misra, Kabita Agarwal, Arun Agarwal, Kuntal Ghosh, **Sumanshu Agarwal**; Smart Antenna for Wireless Cellular Communication-A Technological Analysis on Architecture, Working Mechanism, Drawbacks and Future Scope, 2nd International Conference on I-SMAC, 2018 2, 37-41

[C5]. Ashwin Lele, Saurabh Pinjani, Muhammed Tahir Patel, Vikas Nandal, **Sumanshu Agarwal**, and Pradeep R. Nair; Effect of Interface Charges on the Efficiency of Perovskite based Solar Cells; 43rd IEEE Photovoltaic Specialists Conference (PVSC), **Jun 2016**, 0790 – 0792, Portland, USA.

[C6]. **Sumanshu Agarwal*** and Pradeep R. Nair; Device Characterization and Performance Optimization of Perovskite Solar Cell using Opto-Electronic Modeling; 7th Hybrid and Organic Photovoltaics Conference, **May 10-13, 2015**, Rome, Italy.

[C7]. **Sumanshu Agarwal*** and Pradeep R. Nair; Performance Optimization for Perovskite Based Solar Cells; 40th IEEE Photovoltaic Specialists Conference (PVSC), Jun **2014**, 1515 – 1518, Denver, USA.

Conferences (without proceedings)

[C8]. Suchismita Rout and **Sumanshu Agarwal***; Unraveling the Anomalous Current-Voltage Characteristics in Perovskite-based Solar Cells, International Conference on Advances in Energy, Environment for Sustainable Development, **Jan 2022**, ITER Bhubaneswar, India

[C9]. Suchismita Rout and **Sumanshu Agarwal***; Correlation between S-Shaped IV and Carrier Recombination Velocity at Electrodes in Perovskite-based Thin Film Solar Cells, 3rd Indian Materials Conclave and 32nd AGM of MRSI, **Dec 2021**, IIT Madras, India

[C10]. **Sumanshu Agarwal***, Shaibal K. Sarkar, and Pradeep R. Nair; Device Physics and Performance Optimization of Perovskite Based Solar Cells, Energy Day, **Mar 2017**, IIT Bombay, India.

[C11]. **Sumanshu Agarwal***, Anand S. Subbiah, Pradeep R. Nair, and Shaibal K. Sarkar; Practical Performance Limits of $FAPbBr_3$ Perovskite Solar Cells; 61st DAE Solid State Physics Symposium, **Dec 2016**, KIIT Bhubaneswar, India.

[C12]. **Sumanshu Agarwal***, Shaibal K. Sarkar, and Pradeep R. Nair; Device Physics and Performance Optimization of Perovskite Based Solar Cells; Invited talk at 2nd Mumbai-Pune Semiconductor Meet, **Mar 2016**, IISER Pune, India.

[C13]. **Sumanshu Agarwal*** and Pradeep R. Nair; Roadmap towards High Efficiency (>25%) Perovskite Solar Cells; 18th International Workshop on Physics of Semiconductor Devices, **December 7-10, 2015**, 345, IISc Bangalore, India.

[C14]. **Sumanshu Agarwal*** and Pradeep R. Nair; Device Physics and Efficiency Improvement in Perovskite Solar Cell; National Symposium for Material Research Scholars, **May 20-22, 2015**, IIT Bombay, India.

PROFESSIONAL ACTIVITIES

- Active reviewer for many journals

  Semiconductor Science and Technology, Flexible and Printed Electronics, Journal of Applied Physics, Applied Physics Letters, APL Materials, AIP Advances, Journal of

Renewable and Sustainable Energy, Institution of Engineers India Series-B, Engineering Research Express

- Life Member, Material Research Society of India
- Education head and founding member, NGO MIITTI http://miitti.in/ **Jun 2015–Present**
- **Coordinator** for monthly SERIIUS project group meeting at IIT Bombay Chapter **Jun 2015–Dec 2016**
- Graduate Student Assistant, 40th IEEE Photovoltaic Specialists Conference, Denver USA **Jun 2014**
- Mess Secretary, Hostel – 13, IIT Bombay **Jun 2012–May 2013**
- Coordinator, Poster session, 1st International Conference on Emerging Electronics **Dec 2012**
- Coordinator, Venue management, 3rd International Conference on Advances in Energy Research, IIT Bombay **Dec 2011**
- Member, Publicity, 2nd International Conference on Advances in Energy Research, IIT Bombay **Dec 2009**

EXTRA-CURRICULAR ACTIVITIES

- Performed street play with the theme “Drug Addiction is a Curse” in Powai Fest 2014 **Jan 2014**
- Received organizational special mention award, Hostel – 13, IIT Bombay **2013**
- Limca world record for participating (solving) in largest number of people solving Rubik cube simultaneously **2012**
- Received sports special mention award, Hostel – 13, IIT Bombay **2012**

PCCP

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PAPER

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Cite this: DOI: 10.1039/d1cp02556b

Deciphering the capacitance frequency technique for performance-limiting defect-state parameters in energy-harvesting perovskites†

Vikas Nandal, *[ab] Sumanshu Agarwal *[c] and Pradeep R. Nair *[b]

Received 8th June 2021,
Accepted 11th October 2021

DOI: 10.1039/d1cp02556b

rsc.li/pccp

With emerging thin-film PIN-based optoelectronics devices, a significant research thrust is focused on the passivation of trap states for performance enhancement. Among various methods, the capacitance frequency technique (CFT) is widely employed to quantify the trap-state parameters; however, the trapped charge-induced electrostatic effect on the same is not yet established for such devices. Herein, we present a theoretical methodology to incorporate such effects in the CF characteristics of well-established, but not limited to, carrier-selective perovskite-based PIN devices. We show that the electrostatic effect of trapped charges leads to non-linear energy bands in the perovskite layer, which results in the underestimation of the trap density from existing CFT models. Consequently, a parabolic band approximation with effective length (PBAEL) model is developed to accurately predict the trap density for shallow or deep states from CFT analysis. In addition, we demonstrate that the attempt-to-escape frequency, which dictates the trapping dynamics, can be well extracted by eliminating the electrostatic effect at a reduced perovskite thickness. We believe that our work provides a unified theoretical platform for CFT to extract trap-state parameters for a broad class of organic, inorganic, and hybrid semiconductor-based thin-film devices for energy-conversion applications such as solar cells, LEDs, artificial photosynthesis, *etc.*

1 Introduction

With excellent optical properties, low-cost solution-processed organic and hybrid materials have attracted significant research interest towards the development of optoelectronic devices such as solar cells, LEDs, *etc.*[1–6] The performance of various energy-conversion devices is significantly limited by shallow and deep defect states.[7–11] For instance, free charge carriers in respective continuum energy bands undergo the trapping/de-trapping process with shallow defect states, leading to a reduced charge carrier mobility. By contrast, deep trap states act as Shockley–Read–Hall (SRH) recombination centers and increase the recombination loss of photogenerated charge carriers.[12–16] Therefore, material characterization is imperative for quantifying performance-limiting trap-state parameters like the trap density, trap energy, and attempt-to-escape frequency.

In the literature, depending on device architecture and experimental conditions, various measurements/methods, like the capacitance frequency technique (CFT),[17–19] deep level transient spectroscopy (DLTS),[18,20,21] the thermally stimulated current (TSC),[22–24] capacitance–voltage (CV),[25] and the thermal dielectric relaxation current (TDRC), are employed to obtain the above-mentioned trap-state parameters.[26–28] In particular, CFT is a well-established and widely utilized characterization scheme for emerging organic, inorganic, and hybrid materials, *e.g.*, perovskites.[29–33] Using CFT, Walter *et al.* proposed a linear band approximation (LBA) model $N_l(E)$ for the homogenous PIN diode and a parabolic band approximation (PBA) model $N_p(E)$ for the PN diode to estimate the trap density of a semiconducting material inside the depletion region, and these are approximately given by[17]

$$N_l(E) \approx -\frac{{V_{bi}}^2}{qALkT} f \frac{dC}{df}, \quad (1)$$

$$N_p(E) \approx -\frac{V_{bi}}{qALkT} f \frac{dC}{df}. \quad (2)$$

Here, E is energy with respect to the continuum energy bands, V_{bi}, L, A, T, and C are the built-in voltage, depletion width, cross-sectional area, lattice temperature, and capacitance of the diode, respectively. The constants q, k, and f are the electronic

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† Electronic supplementary information (ESI) available. See DOI: 10.1039/d1cp02556b

Optimal residual subspace model for structural damage diagnosis: an approach independent of operational and environmental variations

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*Corresponding author

Abstract: Several machine learning algorithms have been proposed to detect damage in civil structures that implicitly learn changes in dynamic characteristics of structures due to varying operational and environmental conditions. However, despite the intensive computational load, the methods were not able to completely mitigate the said variations. In contrast to that, here, we introduce a new methodology based on percentage of total variance (PTV) criterion for damage detection to overcome the influence of varying operational and environmental conditions on the vibration-based damage sensitive features. Using PTV criterion, an optimal residual subspace (ORS) is modelled which is applied to Mahalanobis squared distance (MSD) and singular value decomposition (SVD)-based damage detection methods. Interestingly, we find that in comparison with similar machine learning-based damage detection approaches, the proposed approach outperforms in terms of false positive reduction and overall accuracy.

Keywords: structural health monitoring; damage detection; outlier detection; optimal residual space; percentage of total variance; PTV; eigenspace; Mahalanobis squared distance; MSD; singular value decomposition; SVD.

Reference to this paper should be made as follows: Kumar, K. and Agarwal, S. (2022) 'Optimal residual subspace model for structural damage diagnosis: an approach independent of operational and environmental variations', *Int. J. Structural Engineering*, Vol. 12, No. 1, pp.44–61.

Biographical notes: Kundan Kumar received his PhD from the Department of Electronics and Electrical Communication Engineering at Indian Institute of Technology Kharagpur, India. He is an Associate Professor at the Department of Electronics and Communication Engineering, Institute of Technical Education and Research, Siksha 'O' Anusandhan (Deemed to be University). He has published various peer-reviewed research papers and book chapters with national and international publishers. His research interests include structural health monitoring, time series analysis, machine learning and computer vision.

Journal of Applied Physics ARTICLE scitation.org/journal/jap

Antimony chalcogenide-based thin film solar cells: Device engineering routes to boost the performance

Cite as: J. Appl. Phys. **129**, 203101 (2021); doi: 10.1063/5.0047429
Submitted: 13 February 2021 · Accepted: 5 May 2021 ·
Published Online: 24 May 2021

View Online Export Citation CrossMark

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AFFILIATIONS

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[2]Nanomaterials Research Institute, National Institute of Advanced Industrial Science and Technology, 1-1-1 Higashi, Tsukuba, Ibaraki 305-8565, Japan
[3]Department of Mechanical Engineering, Indian Institute of Technology Indore, Indore, Madhya Pradesh 453552, India

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ABSTRACT

The use of stibnite (Sb_2S_3) as a light-harvesting material in thin film solar cells has received considerable research interest during the transition of the millennium. However, the use of perovskite diminished the research in the field, and the potential of antimony Chalcogenides [$Sb_2(S,Se)_3$] was not explored thoroughly. Although these materials also provide bandgap tuning like perovskite, by varying the composition of S and Se, it is not as popular as perovskite for the fabrication of solar cells mainly because of the low efficiency of the solar cells based on it. In this paper, we present a landscape of the functional role of various device parameters on the performance of $Sb_2(S,Se)_3$-based solar cells. For this purpose, we first calibrate the optoelectronic model used for simulation with the experimental results from the literature. The model is then subjected to parametric variations to explore the performance metrics for this class of solar cells. Our results show that despite the belief that the open circuit voltage is independent of contact layers' doping in proper band-aligned carrier selective thin film solar cells, here we observe otherwise and the open circuit voltage is indeed dependent on the doping density of the contact layers. Using the detailed numerical simulation and analytical model, we further identify the performance optimization route for $Sb_2(S,Se)_3$-based thin film solar cells.

I. INTRODUCTION

The late 20th century witnessed rapid research in various solar cell technologies,[1,2] including thin-film[3–5] and multijunction[6] solar cells, and also the dye-sensitized solar cell (DSSC) was invented[7] during that time period. Although initially, DSSCs were supposed to have a promising future,[8] very soon, it was beyond the horizon because of the lack of reproducibility,[9] scalability,[10] and stability[11,12] along with the degrading performance[13] and electrode corrosion.[14] During the same period, the use of Sb_2S_3 in solar cells[15] was demonstrated. However, it took more than a decade to realize its use in carrier selective thin film solar cells.[16] Later on, the material was also used to fabricate photoelectrochemical cells and solid state sensitized solar cells. However, the technology did not draw much attention because of substandard performance characteristics,[17] and the research in the field had been shallow.[18] Contrastingly, exponential growth in the research on perovskite solar cells in the last decade,[19–22] owing to their high performance and reproducibility, has hardly been overlooked by anyone.[23–26] On that account, the research on antimony chalcogenide-based solar cells was not endorsed much, and the technology did not see expected growth.

Nonetheless, a few research groups have reported exciting results in the area[27,28] ranging from bandgap tuning[29] (in the range of 1.1–1.71 eV) and compositional grading of the active layer[30] [by using $Sb_2(S,Se)_3$] to the fabrication of high-efficiency devices[29,31,32] using relatively simple techniques.[33] Despite these encouraging

J. Inst. Eng. India Ser. B
https://doi.org/10.1007/s40031-018-0366-0

REVIEW PAPER

5G Wireless Cellular Networks: A Conceptual Analysis on Perception, Network Requirements and Enabling Technologies

Arun Agarwal[1] · Gourav Misra[2] · Sumanshu Agarwal[1] · Kuntal Ghosh[1]

Received: 22 June 2018 / Accepted: 4 October 2018

Abstract With respect to the upcoming future 5G mobile wireless system generation, some of the key objectives that need to be focused are significant improvement in data rate, increase in capacity, decrease in latency and much better QoS. In modern scientific world, 5G stands in a new row in getting the wireless communication achieved in a smarter and efficient way as compared to the conventional wireless system. This survey paper deliberates to serve as a guideline for the understanding of fifth-generation mobile wireless cellular network perception and network requirements, while pinpointing the enabling technologies in 5G core and wireless network. All these accomplishments would be encouraging universal standardization and increase the rate of research and development toward the innovation of various technologies by collaborating all the contributors in the global 5G ecosystem.

Keywords Data rate · Decrease in latency · QoS · Network requirements · 5G

Introduction

In the 5G forum technology, subcommittee has been playing a vital role in identifying and solving the key features and capabilities of the 5G system. In February 2015, the subcommittee was divided into two different groups such as wireless technology subcommittee and network technology subcommittee. Such separation was made to drive the focus more on essential issues in core networks. The first-generation mobile communication was introduced in the year 1980 for the first time, and a new-generation phone has been introduced in every 10 years roughly. Research and development of each generation was done by either service or requirements in technologies. In the first-generation communication, analog system had played a vital role where only voice communication was possible. From 2G to 3G system, data service had played an important role but the data rate was really limited. However, from third generation to fourth generation, a massive increase in data rate was the primary goal which caused uninterrupted web browsing and video streaming.

Orthogonal frequency division multiple access (OFDMA) was standardized for 4G as an enabling technology and currently deployed as an important MBB infrastructure. The initial vision was set up to 1 Gbps/user data rate to be provided everywhere with hyper-connectivity by the year 2020 [1]. In recent recommendation on framework and overall objectives of the future development of IMT for 2020 and beyond by ITU-R Working Party 5D (WP5D) [2], three different usage scenarios have been identified for 5G as enhanced mobile broadband (eMBB), ultra-reliable and low latency communications (uMTC), massive machine-type communication (mMTC) and use of millimeter wave (mm) [3].

Some specific technical requirements have been identified from the high-level service prospective derived by 5G subcommittee [1]. Eleven key performances have been found out for 5G where most of them were defined for wireless network and one of them (reliability) was identified for core network. The expectation of 5G network is to provide a data rate beyond 20 Gbps, and a minimum data rate of 100 Mbps to 1 Gbps should be provided to each

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JOURNAL OF APPLIED PHYSICS **124**, 183101 (2018)

Performance loss analysis and design space optimization of perovskite solar cells

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(Received 10 July 2018; accepted 18 October 2018; published online 9 November 2018)

While the performance enhancement witnessed in the field of perovskite solar cells over the recent years has been impressive, a detailed analysis of various loss mechanisms is required for further performance optimization. Here, we address the same through numerical simulations of optical and electrical characteristics. We quantify various losses like optical losses (5%–6%), recombination losses (3%–4%), and resistive losses against the Auger recombination induced practical efficiency limits. Through this, we identify schemes to reduce these losses and hence lead to an increase in efficiency. In addition, we find that the optimum thickness of the perovskite (with material parameters comparable to $MAPbI_{3-x}Cl_x$ and Eg = 1.55 eV) for solar cell fabrication is around 300 nm (comparable to the well-established value); however, the same could be as large as 900 nm for a trap free perovskite (~ms as the minority carrier Shockley-Read-Hall recombination lifetime). The analyses also enable us to provide the design charts that could lead to >25% efficient perovskite solar cells on the planar structure. *Published by AIP Publishing.*
https://doi.org/10.1063/1.5047841

I. INTRODUCTION

Solar photovoltaics (PV) is regarded as one of the most promising renewable energy technologies and is expected to play an important role towards meeting the ever-increasing global energy needs. Perovskite solar cells (PSC) are a new class of solar cells in this field and has already achieved >22% efficiency.[1–3] The ambipolar nature of carrier transport with diffusion lengths being more than 1 μm[4–7] and very large extinction coefficients[8–10] makes perovskites an ideal material for photovoltaics. Moreover, perovskites can be deposited using relatively simple techniques like spin coating.[11–14] While the initial research in the field was inclined toward the use of mesoporous TiO_2 scaffold to facilitate electron collection,[15,16] the use of a planar structure (without compromising the performance)[4] simplified the fabrication of the device. Furthermore, the use of mixed perovskites as active material in solar cells has also been reported, and it is shown that the use of Rb in the mixed perovskite results in efficiency as high as 21.6%.[1] There have been many exciting developments in the field of PSCs other than the fabrication of high efficiency devices,[1,17–19] like bandgap tuning,[20] theoretical investigations on the physical mechanisms that govern the performance,[21–24] and design and fabrication of tandem solar cells based on perovskites.[25–29] The presence of mobile ion vacancies and ionic movement has been speculated in these devices.[30–32] The analysis of (a) hysteresis in the JV characteristics and (b) performance variation in degraded devices through drift-diffusion simulations[33,34] and experiments[35–37] further strengthened the arguments. However, the steady state loss analysis and performance optimization calculations,[24,38] even in the absence of the mobile ion vacancies, have resulted in important insights. Although research in the field of PSC is supported by the numerous such theoretical investigations, detailed analyses of different detrimental aspects for PSCs is a topic of immense interest to the community for further design space optimization. In this context, here we provide a comprehensive study of optical and electrical losses in planar perovskite solar cells.

We note that there have been a few recent reports on loss analysis of perovskite solar cells—although with some limitations. For example, loss analysis reported in Refs. 23 and 24 lacks the identification of optimal thickness. On the other hand, thickness optimization reported in the literature[21,39] lacks the quantification of losses due to the different mechanisms. Specifically, carrier recombination in the bulk of perovskites was neglected by Sun *et al.*,[21] which is not an entirely valid assumption. Furthermore, they predict that the efficiency is invariant with active layer thickness beyond a certain value for p-i-n structures, while, on the contrary, there are experimental results which indicate that efficiency peaks for certain active layer thickness.[40–42] Minemoto *et al.*[39] performed thickness optimization calculations considering only SRH (Shockley-Read-Hall) recombination in the active layer along with doped layers. In contrast, here we compute the optimal thickness by combining both optical and electrical modeling with explicit consideration of all three types of

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