Chaotic signatures of photoconductive Cu$_2$ZnSnS$_4$ nanostructures explored by Lorenz attractors

M A Hernández-Acosta$^1$, M Trejo-Valdez$^2$, J H Castro-Chacón$^3$, C R Torres-San Miguel$^1$, H Martínez-Gutiérrez$^4$ and C Torres-Torres$^1$

$^1$ Sección de Estudios de Posgrado e Investigación, Escuela Superior de Ingeniería Mecánica y Eléctrica Unidad Zacatenco, Instituto Politécnico Nacional, Ciudad de México, 07738, México
$^2$ Escuela Superior de Ingeniería Química e Industrias Extractivas, Instituto Politécnico Nacional, Ciudad de México, 07738, México
$^3$ CONACyT-Instituto de Astronomía Universidad Nacional Autónoma de México, Ensenada, Baja California, 22860, México
$^4$ Centro de Nanociencias y Micro y Nanotecnologías, Instituto Politécnico Nacional, Ciudad de México, 07738, México

E-mail: ctorrest@ipn.mx and crstorres@yahoo.com.mx

Keywords: nonlinear optics, two-wave mixing, chaotic attractors, electrochemical impedance spectroscopy

Abstract

Photoconductive and third-order nonlinear optical properties exhibited by Cu$_2$ZnSnS$_4$ nanostructures are presented. The samples were synthetized in thin film form by a spray pyrolysis processing route. Distinctions in the photoconductive behavior throughout the samples were clearly noted by modulating their optoelectronic response dependent on electrical frequency. Vectorial two-wave mixing experiments were carried out at a 532 nm wavelength provided by a Nd:YAG laser system to study the optical nonlinearities in the samples. An induced transparency effect was observed during nanosecond single-beam experiments in the nanostructures reported. Quantum and thermal processes were considered to be the main physical mechanism responsible for the photo-electrical phenomena and nonlinear refraction in the nanostructures. Potential applications for developing nanophotonic and nanoelectronic instrumentation systems can be contemplated.

1. Introduction

The origin of uncertainties that invariably exist during the characterization of physical properties in composite materials usually emerges from the micro and nanostructural scale. Besides, the phenomenological processes responsible for advanced functions currently require the development of complex models [1]. It is for these reasons that in order to facilitate the measurement of multifunctional effects, high-sensitive techniques are mandatory. Particularly, the behavior of chaotic systems seems to be an attractive alternative for sensing analysis by considering their strong dependence on initial conditions [2]. Several applications in various physical fields are assisted by chaotic models [3].

One of the most important considerations for designing high-precision instruments is their sharpness to identify information, noise, and errors from measurements taken in laboratory conditions. Advanced materials with fascinating effects derived from plasmonic or quantum confinement phenomena have proven their power for low-dimensional signal sensing [4, 5]. However, the exceptional dependence of optical and electronic properties on nanoscale morphology causes a significant challenge in order to obtain repeatability and reproducibility in high-precision technologies for industry [6].

On the other hand, through nonlinear dynamics, chaotic systems may increase sensitivity in the detection of variations with respect to a reference measurement [7]. There are numerous applications that involve the prediction of wave parameters by considering chaotic solutions [8]. In this direction, the use of chaos and noise analysis has been assumed to be effective for evaluating the evolution of particular physical properties [9].

Apparently, the integration of different elements in nanocompounds can improve the optical response of specific materials in comparison to the action that they separately present [10, 11]. Some advantages for energy...
transfer and the addition of resonant frequencies can be obtained in nanohybrids resulting from the incorporation of nanoparticles in nanostructured samples [12].

Quaternary semiconductor materials, like Cu2ZnSnS4, have been proposed for the enhancement of photoenergy conversion operations [13]. Important advantages in the use of Cu2ZnSnS4 materials are their low-cost, abundance, non-toxicity and photovoltaic response [14]. Polycrystalline Cu2ZnSnS4 samples have shown a noticeable modification in their electrical and photo-electrical features with dependence on temperature processes [15]. Comparatively, studies about nanostructured Cu2ZnSnS4 seems to be attractive taking into account the facilities to tailor their characteristics by using candidates grouped by constituent elements rather than underlying crystal structures [16]. It can be mentioned that quantum effects in Cu2ZnSnS4 can be employed for luminescent applications [17] and in optoelectronics [18, 19], where a new quaternary phase has been discerned. It can be pointed out that the processing method for preparing Cu2ZnSnS4 materials plays a key role to determine the characteristics in real applications [20, 21].

In view of these considerations, this work has been devoted to further investigate the conductive effects induced by light in Cu2ZnSnS4 nanostructures. A modulation of electrical signals following a chaotic behavior was carried out for exploring the samples in a high-sensitive fashion. Third-order nonlinear optical interactions were analyzed by nanosecond pulses. In regards to the results exhibited by the samples prepared in a thin solid film configuration, the development of nonlinear photo-electrical systems and all-optical switching nanodevices can be contemplated.

2. Materials and methods

2.1. Sample synthesis

The samples were synthesized by using a standard spray pyrolysis deposition technique. Compressed air was used as the carrier gas in a 2 ml min⁻¹ fixed flux. The precursor solution was based on CuCl₂ · 2H₂O, CH₃COOH, 2Zn · 2H₂O, SnCl₄ · H₂O and thiourea. Firstly, 1 mmol of SnCl₄ · H₂O salt was dissolved in a glass vessel containing 50 ml of aqueous hydrochloric acid solution 2% v/v. This solution was stirred for 10 min and subsequently a volume of 50 ml of aqueous zinc acetate (0.0045 M) was incorporated. The obtained solution was stirred for 3 min and 50 ml of aqueous CuCl₂ (0.009 M) was poured into the mixture. The stirring step continued for 15 min and 50 ml of thiourea solution (0.05 M) was finally poured into the whole solution. The resulting precursor solution was transparent and stable with no solid formation for at least one day. In order to prepare the thin films, commercial soda-lime glasses in a fused tin bath at 420 °C were employed as substrates. The deposition time of the precursor solution was systematically studied to obtain films with thickness close to 1 μm. Samples with 2.5 h of deposition time were selected to present this report. Scanning electronic microscopy (SEM) studies were undertaken by using a FEI Quanta 3D FEG Microscope system in scanning transmission electron microscopy (STEM) mode. Compositional analysis was conducted by energy dispersive x-ray spectroscopy (EDS) by using a JEOL JSM-7800F system in STEM mode. A Perkin Elmer XLS UV–visible spectrophotometer was employed to observe the characteristic optical spectrum of the films.

2.2. Electrical and photoconductive studies

An Autolab PGSTAT302N potentiostat galvanostat was used for measuring the electrical impedance of the samples. A Wheatstone bridge configuration with a modulation of the electrical signal governed by a Chua circuit model was employed in this study [22]. The Chua circuit equations can be written as [23]:

\[
\frac{dx}{dt} = G_1[y - x - F(x)], \quad (1)
\]

\[
\frac{dy}{dt} = x - y + z, \quad (2)
\]

\[
\frac{dz}{dt} = C_2y \quad (3)
\]

with:

\[
F(x) = m_1x + 0.5(m_0 - m_1)(|x + 1| - |x - 1|) \quad (4)
\]

here \(x, y\) and \(z\) denote the state variables of the system, \(C_1\) and \(C_2\) are the system parameters, and \(F(x)\) was selected to represent the piecewise-linear function:

\[
F(x) = \begin{cases} m_1(x + 1) - m_0 & x \leq -1, \\ m_0 & -1 < x \leq 1, \\ m_1(x - 1) & 1 < x \end{cases} \quad (5)
\]
It is worth noting that for the case that the condition $m_1 < -1 < m_0$ is satisfied, the system presents stability. We employed the code for using a Labview software with $A = 10; B = 14.87; m_1 = -1.27; m_0 = -0.68$ [22–24], in order to control a 5 V signal in the electrical measurements of the conductivity and photoconductivity of the sample. Two well-defined orbits describing a chaotic voltage behavior can be obtained following the conditions for stability. The photoconductivity of the films was induced by using a Nd:YAG laser system at 532 nm wavelength, 5 ns pulses, 350 mJ of maximum energy per pulse and a spot size of 1 mm as illustrated in figure 1. The resistances, $r_{x,3}$, in the schematized Wheatstone bridge presented a magnitude of approximately 220 kΩ. The resistance, $r_x$, corresponds to the impedance of the sample studied and $V$ represents the electrical points for recording the data. Diverse regions of the samples were explored by carbon electrodes deposited in direct contact with the nanostructures. A comparison of the different measurements was performed by continuous and modulated electrical signals.

2.3. Nanosecond third-order nonlinear optical measurements

The transmittance of the sample was monitored during the photo-electrical studies in order to identify any potential nonlinear optical absorption phenomenon. Moreover, a vectorial two-wave mixing experiment was implemented to analyze the third-order optical nonlinearities in the nanostructures, as illustrated in figure 1 [25]. A geometrical angle of 45° was measured between the pump and probe beams impinging into the sample. The intensity relation 1:10 for the pump and probe beams was hold during the measurements with the second harmonic pulses provided by our nanosecond Nd:YAG laser system with 100 mJ pulse energy. The linear polarization of the probe beam fixed while the polarization of the pump beam was rotated by using a half-wave plate, represented by $\lambda/2$ in the draw. A polarizer was located before the PIN photodetector for testing any modulation of the polarization associated with the probe signal. The transmittance axis of the polarizer was crossed in respect to the initial polarization of the probe beam when the pump beam was absent. A digital oscilloscope, Osc, allowed the acquisition of the transmitted beam data.

For describing the propagation of the pump and probe beams, we used the finite-differences method to numerically solve the wave-equation [26]:

$$\nabla^2 E_n = -\frac{n^2 \omega^2}{c^2} E_n, \quad (6)$$

where the right and left circular components of the electric field were considered as $E_+$ and $E_-$, respectively. The optical frequency was $\omega$ and the approximation for the correspondent refractive index, $n_{\pm}$, was expressed as [26]:

$$n_{\pm}^2 = n_0^2 + 4\pi (A |E_\pm|^2 + (A + B) |E_\mp|^2), \quad (7)$$

where $A = \chi^{(3)}_{1122}$ and $B = \chi^{(3)}_{1212}$ and $n_0$ is the weak-field refractive index.

3. Results and discussions

Figure 2(a) shows a panoramic SEM image of the film where it can be clearly observed an inhomogeneous morphology with randomly distributed needle-like particles. The thickness of the studied films was close to
μm as it can be seen from a representative SEM image in the inset. The statistical SEM estimations pointed out an average size of the needles in the samples to be approximately 290 nm width and 11.17 μm length. In figure 2(b) is depicted the EDS data exhibited by a region in the nanostructures with the inset showing with a red circle the point of measurement in a SEM micrograph.

Figure 3 shows the optical absorption spectrum of the samples. This data matches with previous measurements in comparative samples [27, 28]. In the ultraviolet region, close to 300 nm wavelength can be observed a well-defined peak associated with the SiO2 substrate absorbance. The color of the sample was reddish brown. The bandgap of the Cu2ZnSnS4 nanostructures according to the tangent of the slope in the absorbance spectrum [29, 30] was estimated to be around 600 nm

\[(\alpha hv)^2 = A(hv - E_g),\]  

where \(\alpha\), \(A\), \(E_g\), and \(\nu\) represent the absorption coefficient, proportionality constant, bandgap energy, and light frequency; respectively.

The calibration of the electrical measurements was conducted by monitoring the correlation of Lorenz attractors generated by numerous reference measurements related to electrical conductivity. Different regions of the film samples were studied keeping constant the separation for the electrodes equal to 2.5 mm ± 1 μm. From figure 4(a) can be visualized a remarkable change in the correlation of the chaotic signals originated by a variation in the electrical conductivity examined. The stable behavior in the plot corresponds to a conductivity
value of 2.19 $\mu\Omega^{-1}$ of the characterized nanostructures in darkness; while the unstable curve represents a change of 2.37% in their conductivity magnitude induced by light. The correlation between these signals was 0.976.

Figure 4 shows two particular frequency spectra of the chaotic electrical signals testing the sample in darkness and under the irradiation of nanosecond pulses at a 532 nm wavelength. Frequency spectra were obtained by applying the fast Fourier transform to the corresponding time signals; time series consisting of 1024 points were acquired for this purpose.

Some important physical factors able to modify electrical conductivity in a material are related to energy deposited by temperature or electromagnetic fields. Besides, the dynamics of the electrical energy in propagation through a material must be also taken into account to determine the performance of electronic communication systems. Figure 5(a) exemplifies important variations in the conductivity of the sample when the electrical signal was modulated with a chaotic behavior. In regards to the noteworthy modifications in the conductivity evaluated by a chaotic modulation, it was analyzed the electrical response of the sample dependent on electrical frequency. Figure 5(b) shows the impedance spectrum of the nanostructures studied. As it can be seen from the data plotted in figure 5(b), the reduction of the electrical impedance as a function of the electrical frequency pointed out a capacitive behavior emerging in the electrical behavior of the sample. The decrease of electrical impedance for the sample under irradiation suggests a photoconductive effect that may be generated by a photonic mechanism.
Figure 6 shows the photoconductivity dependent on optical irradiance in the film. During the experiments was verified that the photoconductivity was insensitive to the polarization of the optical beam. However, an abrupt increase in the photoconductive effect can be seen when high-irradiance is in propagation through the sample. The use of a chaotic modulation seems to discriminate stronger changes of photoconduction that should be associated with the dependence on electrical frequency of the nanostructures.

Nonlinear optical absorption effects were explored by using a single-beam transmittance experiment with nanosecond pulses. Figure 6(b) shows the transmitted optical irradiance describing a typical induced transparency that can be related to a saturated absorption effect.

It has been previously reported that a chaotic modulation in continuous wave optical irradiation gives origin to important identification related to optical transmittance information [31]. The nonlinear optical effects exhibited by chaotic modulation of nanosecond pulses is a good challenge for developing high-sensitive ultrafast systems assisted by nonlinear optics. In this research, we focused on the chaotic modulation of electronic signals for exploring photoconductive effects as it is shown in figure 6(a). The data plotted in figure 6(b) allowed us to guarantee that nonlinear optical absorption takes place during the photoconductive experiments explored by nanosecond pulse irradiation. For further investigate the nonlinear optical response exhibited by the nanostructures, two-wave mixing explorations were conducted with the experimental setup described in figure 1. The process of two-wave mixing produces an interference pattern where bright irradiance fringes have a strong field which triggers third-order nonlinear optical phenomena, as the optical Kerr effect. The optical Kerr effect induces a birefringence when optical irradiance is strong and the waves are in propagation through a given material. The change in refractive index can be described by $\Delta n = n_2 I$, where $n_2$ is the nonlinear refractive index and $I$ is the incident optical irradiance. The optical Kerr effect is called so by analogy with the traditional Kerr electrooptic effect; in which the refractive index of a material changes by a magnitude that is proportional to the square of the strength of an applied static electric field [26]. According to our estimations, a pure electronic response is responsible for the picosecond birefringence induced in the sample.

Comparative two-wave mixing experiments were performed by using picosecond pulses at a 532 nm wavelength. The self-diffraction efficiencies calculated as the rate of first and zero order of diffraction in the experiment were analyzed. Normalized experimental data (marks) and numerical curves calculated by equation (6) are plotted in figure 8. The relation between maximum orthogonal components of polarization of the self-diffraction signals led us to categorize the physical mechanism of nonlinear refraction by adjusting in equation (7) the relation $B/A = 0$ for thermal effect, $B/A = 1$ for electronic response or $B/A = 6$ for molecular orientation [26]. According to our estimations, a pure electronic response is responsible for the picosecond birefringence induced in the sample.
photoconductivity induced by picosecond pulses with the same wavelength and energy. It can be considered that a photo-electrical response induced by nanosecond pulse illumination can excites electron–hole pairs, and the electrons can be recombined in the interface states, collected at the surface potential or recombined in the intracrystalline semiconductor region with dependence on temperature.

There has been reported attractive electrostatically driven applications related to engineering chaotic motion in nanostructures [32]. Particular composite materials for developing optomechanic operations based on chaotic systems [33] and nonlinear dynamics in optomechanically-controlled beams have been proposed [34]. Memory applications based on electrical parameters in nanostructures have been pointed out as an alternative for developing nanoscale superconducting phenomena [35]. Specially, advantages for Cu2ZnSnS4 solar cell functions have been suggested [36]. The assistance of chaotic effects in the temporal dynamics exhibited by all-optical nanodevices seems to be suitable [37, 38].

Figure 7. Transmitted Kerr irradiance as a function of the angle between the planes of polarization of the interacting beams.

Figure 8. Picosecond self-diffraction efficiency as a function of the angle between the planes of polarization of the interacting beams.
Regarding the outstanding optical response exhibited by materials with a large area/volume fraction and the importance of the initial conditions for chaotic systems, this work is highlighted the potential of a chaotic signal modulation for evaluating photo-electrical properties exhibited by nanostructures.

4. Conclusions

A significant enhancement in the sensibility for analyzing photovoltaic effects in nanostructures was proposed by using a chaotic modulation of electrical signals. Quantum transitions and thermal processes were considered as the main physical mechanisms responsible for the photoconductivity and third–order nonlinear optical properties exhibited by the studied samples by using ultrafast pulses. The electrical dependence on the frequency of the studied nanostructures allowed us to indicate that slight discrepancies on structure and optical properties exhibited by the studied samples by using ultrafast pulses. The electrical dependence on the frequency of the studied nanostructures allowed us to indicate that slight discrepancies on structure and optical properties exhibited by the studied samples by using ultrafast pulses.

Acknowledgments

The authors kindly acknowledge the financial support from Instituto Politécnico Nacional, and from Consejo Nacional de Ciencia y Tecnología (CB-2015-251201). The authors are also thankful to the Central Microscopy facilities of the Centro de Nanociencias y Micro y Nanotecnologías del Instituto Politécnico Nacional.

ORCID iDs

C Torres-Torres @ https://orcid.org/0000-0001-9255-2416

References

[1] Naskar S, Mukhopadhyay T, Siramula S and Adhikari S 2017 Stochastic natural frequency analysis of damaged thin-walled laminated composite beams with uncertainty in micromechanical properties Compos. Struct. 160 312–34
[2] Thapa M, Mulani S B and Walters R W 2018 A new non-intrusive polynomial chaos using higher order sensitivities Comput. Methods Appl. Mech. Eng. 328 594–611
[3] Arwas G and Cohen D 2016 Chaos and two-level dynamics of the atomtronic quantum interference device New J. Phys. 18 015007
[4] Roh S, Chung T and Lee B 2011 Overview of the characteristics of micro- and nano-structured surface plasmon resonance sensors Sensors 11 1365–88
[5] Li Y, Yan H, Farmer D B, Meng X, Zhu W, Osgood R M, Heinz T F and Avouris P 2014 Graphene plasmon enhanced vibrational sensing of surface-adsorbed layers Nano Lett. 14 1573–7
[6] Xu H, Kan C, Miao C, Wang C, Wei J, Ni Y, Lu B and Shi D 2017 Synthesis of high-purity silver nanorods with tunable plasmonic properties and sensor behavior Photonics Res. 5 27–32
[7] Dai H, Zhao S and Chen K 2017 A chaos-oriented prediction and suppression model to enhance the security for cyber physical power systems J. Parallel Distrib. Comput. 103 87–95
[8] Ghorbani M A, Asadi H, Makarynskyy O, Makarynska D and Yaseen Z M 2016 Augmented chaos–multiple linear regression approach for prediction of wave parameters Eng. Sci. Technol., Int. J. 20 1180–91
[9] Mahjani M G, Mosshrefi R, Sharifi Viand A, Taherzad A and Jafarian M 2016 Surface investigation by electro chemical methods and application of chaos theory and fractal geometry Chaos Solitons Fractals 91 598–603
[10] I m J H, Lee C R, Lee J, Park S W and Park N G 2011 6.5% efficient perovskite quantum-dot–sensitized solar cell Nanoscale 3 4088–93
[11] Kim H S, Lee C R, Im J H and Lee K B 2012 Lead iodide perovskite sensitized all-solid-state submicron thin film mesoscopic solar cell with efficiency exceeding 9% Sci. Rep. 2 391
[12] Raino R, Stolferle T, Park C, Kim H, Topuria T, Rice P M, Chin J, Miller R D and Mahrt R F 2011 Plasmonic nanohybrid with ultrasmall Ag nanoparticles and fluorescent dyes ACS Nano 5 3536–54
[13] Miyashita M, Hanayama T, Atarashi D and Sakaï E 2012 Photenergy conversion in p-type Cu2ZnSnS4 nanorods and n-type metal oxide composites J. Phys. Chem. C 116 23945–50
[14] Dilsaver P S, Reichert M D, Hallmark B L, Thompson M J and Vela J 2014 Cu2ZnSnS4–Au heterostructures: toward greener chalcogenide-based photocatalysts J. Phys. Chem. C 118 21226–34
[15] Ashrafi M, Abdel-Rahman M M and Badr A M 2003 Photocconductivity of TiGaSe2 layered single crystals J. Phys. D: Appl. Phys. 36 109–13
[16] Zawadzki P, Baranowski J L, Peng H, Toberer E S, Ginley D S, Tumas W, Zakutayev A and Lany S 2013 Evaluation of photovoltaic materials within the Cu–Sn–S family Appl. Phys. Lett. 103 253902
[17] Marques-Prieto J A, Levenco S, Hampel H and Fober I 2016 Earth abundant thin film solar cells from co-evaporated Cu2SnS3 absorber layers J. Alloys Compd. 689 182–6
[18] De Trizio L, Prato M, Genovese A and Casu A 2012 Strongly fluorescent quantumary Cu–In–Zn–S nanocrystals prepared from Cu2, InSn nanocrystals by partial cation exchange Chem. Mater. 24 2400–6
[19] Gonzalez J C, Ribiero G M, Viana E R, Fernandes P A, Salome P M P, Gutierrez K, Abellido A, Matinaga F M, Leitao J P and da Cunha A F 2013 Hopping conduction and persistent photocconductivity in Cu2ZnSnS4 thin films J. Phys. D: Appl. Phys. 46 155107
[20] Shin B, Gunawan O, Zhu Y, Bojarczuk N A, Chey S J and Guha S 2013 Thin film solar cell with 8.4% power conversion efficiency using an Earth-abundant Cu2ZnSnS4 absorber Prog. Photovolt., Res. Appl. 21 72–6

[21] Shinde N M, Dubal D P, Dhawale D S, Lokhande C D, Kim J H and Moon J H 2012 Room temperature novel chemical synthesis of Cu2ZnSnS4 (CZTS) absorbing layer for photovoltaic application Mater. Res. Bull. 47 302–7

[22] Mamat M, Sanjaya M and Maulana D S 2013 Numerical simulation chaotic synchronization of Chua circuit and its application for secure communication Appl. Math. Sci. 7 1–10

[23] Recai K 2010 A Practical Guide for Studying Chua’s Circuits (World Scientific Series on Nonlinear Science Series A vol 71) (Singapore: World Scientific)

[24] Méndez-Ramírez R, Arellano-Delgado A, Cruz-Hernández C and Martínez-Clark R 2017 A new simple chaotic Lorenz-type system and its digital realization using a TFT touch-screen display embedded system 2017 6820492

[25] Piña-Díaz A J, Trejo-Valdez M, Morales-Bonilla S, Torres-San Miguel C R, Martínez-González C L and Torres-Torres C 2017 Nonlinear mechano-optical transmittance controlled by a rotating TiO2 thin solid layer with embedded bimetallic Au–Pt nanoparticles J. Nanomater. 2017 2918509

[26] Boyd R W 1992 Nonlinear Optics (San Diego, CA: Academic)

[27] Henry J, Mohanraj K and Sivakumar G 2016 Electrical and optical properties of CZTS thin films prepared by SILAR method J. Asian Ceram. Soc. 4 81–4

[28] Guo B L, Chen Y H, Liu X J, Liu W C and Li A D 2014 Optical and electrical properties study of sol–gel derived Cu2ZnSnS4 thin films for solar cell J. Nanopart. Res. 4 097115

[29] Wang J, Zhang P, Song X and Gao L 2014 Cu2ZnSnS4 thin films: spin coating synthesis and photoelectrochemistry RSC Adv. 4 21318–24

[30] Scragg J J, Daleb P J and Peter L M 2008 Towards sustainable materials for solar energy conversion: preparation and photoelectrochemical characterization of Cu2ZnSnS4 Phys. Status Solidi b 6 359

[31] Muñoz-César J C, Torres-Torres C, Moreno-Valenzuela J, Torres-Torres D, Urrigolagotia-Sosa G and Trejo-Valdez M 2013 Identification of inhomogenous optical absorptive response by chaotic photonic signals in Au nanoparticles Meas. Sci. Technol. 24 035603

[32] Chen Q, Huang L, Lai Y-C, Grebogi C and Dietz D 2010 Extensively chaotic motion in electrostatically driven nanowires and applications Nano Lett. 10 406–13

[33] Bakemeier L, Alvermann A and Fehske H 2015 Route to chaos in optomechanics Phys. Rev. Lett. 114 013601

[34] Navarro-Urrios D, Capuj N E, Colombano M F, García P D, Sledzinska M, Alzina F, Griol A, Martínez A and Sotomayor-Torres C M 2016 Nonlinear dynamics and chaos in an optomechanical beam Nat. Commun. 8 14965

[35] Murphy A, Averin D V and Bezryadin A 2017 Nanoscale superconducting memory based on the kinetic inductance of asymmetric nanowire loops New J. Phys. 19 063015

[36] Liu Y, Yan C, Sun K, Zhou F, Hao X and Green M A 2017 Light-bias-dependent external quantum efficiency of kesterite Cu2ZnSnS4 solar cells ACS Photonics 4 1684–90

[37] Sciamanna M and Shore K A 2015 Physics and applications of laser diode chaos Nat. Photon. 9 151–62

[38] Chui C-P, Jiang X-W, Chang K-C and Wei M D 2017 Chaos and extreme events in an azimuthally polarized Nd:GdVO4 laser with pump modulation Opt. Lett. 42 423–6