Warszawa, 15.07.2021

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Referee report on PhD thesis "**Light Interactions with Periodic Nanoline Arrays for Nanoelectronic Applications**" by Andrzej Gawlik

The thesis reports on the properties of periodic nanoline arrays, which constitute important building blocks of shrinking logic devices. At present, it is unclear which are the best measurement methods suitable to evaluate the nanometre-scale features of such devices and how the industrial requirements will affect the required metrology. One of the promising candidate for the metrology of nanoline-based devices are optical techniques. However, for their implementation it is necessary to fully understand the mechanisms of the light interactions with periodic nanoline arrays. The importance of the understanding of the light interactions with nanoline arrays is not limited to the development of non-contact characterisation techniques. The laser light can be also used in manufacturing technology of new generation of 3D devices. The introduction of these optical techniques in a manufacturing technology is still very challenging, as they rely on the efficiency of the light coupling and absorption inside nm-scale arrays, which are strongly geometry-dependent.

The main goal of the thesis is the development of the fundamental physical understanding of the light interaction with nanoline arrays. The thesis focuses on the impact of geometry on the light interactions with periodic nanoline arrays and their size-dependent optical properties. Developed theoretical models are verified by experiment. The study provides in-depth insight into physical properties of periodic nanoline arrays. The topic of the thesis, apart from unquestionable scientific value, is highly relevant for development of future devices.

The thesis consists of 7 chapters, 2 appendices and covers 280 pages. The list of references includes 173 items. The extent of the thesis corresponds to its significance and amount of new knowledge it presents. The significant results of the author's research work have been already published in renowned scientific journals and presented at the conferences representative to the field of study.

The original author's results are preceded by the discussion of the fundamental concepts describing the light propagation and interactions with homogenous isotropic and uniaxially anisotropic media (Chapter 2), followed by the introduction of basic tools for qualitative understanding of light propagation in periodic nanoline arrays.

Chapter 3 develops a semi-analytical optical model for the light interaction with periodic nanoline arrays, allowing for calculation of reflectance, transmittance and integrated electric field coupled into the nanolines. The model, derived in the thesis is more rigorous as compared to classical effective medium theory EMT but still retains its simplicity, which makes it competitive to computationally heavy, numerical or modal methods. The model is based on the conventional mode matching technique MMT, with assumption that the light interaction with the array can be approximated by the coupling between the dominant diffraction mode and the dominant (not necessarily fundamental) waveguide array mode. The array is replaced by an effective homogenous uniaxial medium, whose optical properties are fully characterized with a complex effective refractive index tensor. The strength of the author's model is in its ability to develop fundamental intuition on the light interactions with periodic nanoline arrays. The developed semi-analytical model is used in subsequent chapters of the work to explain the impact of geometry on the light interaction with nanoline arrays.

In Chapters 4 and 5 impact of geometric parameters, i.e. width CD, pitch Λ and height h of nanoline on the light interaction with nanoline array is investigated. The different nanoline materials are considered; perfect electric conductor, metal, semiconductor and dielectric, all embedded in an SiO_2 spacer and placed on Si substrate. In Chapter 5 the study for Si nanoline arrays with industrially relevant dimensions is reported.

To understand how the optical response of the structure varies with geometry author introduces the concept of superimposed band structure. Such superimposed band structure encompasses all the information concerning the light propagation outside and inside a periodic nanoline array. The periodicity of the problem allows to restrict computational domain to a unit cell containing one nanoline of width CD and height h embedded into a spacer of pitch Λ and enclosed by two semi-infinite media from the top and the bottom (air and silicon, respectively). The computation were implemented in the Wave Optics Module of the commercial FEM software COMSOL Multiphysics.

In Chapter 6 the model developed in preceding sections is used for quantitative explanation of optical experiments carried out on periodic arrays of semiconducting and metallic nanolines of varying geometry. The comparison between the experimental and theoretical results allowed for (i) validation of the correctness of the model against real nanostructures, (ii) validation of the theoretical predictions made on the base of the model, (iii) extension of applicability of the existing metrology tools, e.g. Raman spectroscopy towards metrology of metallic nanolines. From the point of view of experimental developments demonstration of the capabilities of Raman spectroscopy for probing small variation of critical dimension CD of metallic nanoline arrays is particularly important. As being more sensitive to variations in CD than the commercially used reflectance-based techniques, Raman spectroscopy reveals potential to become a routine CD metrology tool for applications in nanoelectronics. The Raman spectroscopy has been also proved to be applicable for stress/composition analysis of nanodevices.

The final Chapter 7 summarizes the major achievements of the thesis and provides some recommendations for the future works. Among them are suggestions concerning further development of the model, (i) extension of the model towards horizontal nanowire arrays, (ii) extension of the model towards vertical nanowire arrays. Based on the intuitions provided by the standard model the author's suggestion is to treat the above cases as the multilayered nanoline array composed of vertically stacked effective homogenous thin-films and as the single effective homogenous thin-film with excitable modes of circular symmetry, respectively.

The thesis is supplemented with Atlas of Band Structures containing all the band structures of different nanoline arrays with varying pitch Λ and CD, discussed in Chapter 4 and Atlas of Electric Field Distributions for all above structures. Both Appendices are very useful for developing understanding of the results of analyses presented in Chapter 4 of the thesis.

The importance and the novelty of the thesis lies in developing physical model of light interactions with periodic nanoline arrays and combining advanced electromagnetic modeling with experimental results for real nanodevices. This has allowed for a new insight into their functionality and opened possibility for improved optical metrology of devices with 3D architectures. The thesis demonstrates high competence of the author in optics and nanophotonics. The thesis represents truly world class research in the field. The thesis is well organized and clearly written. The content of each chapter is summarized at the end which helps in gathering the most important conclusions.

I am fully convinced that the thesis represents significant and original contribution to the scientific field it deals with. The goals of the thesis have been achieved and its results can be useful both for basic science and applications.

In my opinion the thesis fulfills all requirements posed on theses aimed for obtaining degree of Doctor of Philosophy (PhD) in Physics and I highly recommend it to be accepted and admitted to public defense. On the basis of its contribution to the development of electromagnetic modeling of nanostructures and metrology of modern nanoelectronic devices I recommend thesis to be distinguished.