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On the mechanical behaviour of a crystalline undulator

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ABSTRACT

A crystalline undulator is a newly proposed compact device to generate coherent electromagnetic waves. The crystalline undulator is a micro-electro-mechanical system that relies on silicon micro-fabrication. In the present work, the mechanical behaviour of a crystalline undulator with sub-millimetric period obtained by patterning the surfaces of a silicon lamina with alternate strips has been investigated. The anisotropy of the silicon substrate and the geometrically nonlinear behaviour of the device have been discussed. Sensitivity study has been performed for defining the optimal thickness and width of the strips. Finally, an analytical model is proposed to evaluate the displacements and local effects such as interfacial shear stress concentrations.

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1. Introduction

An undulator is a device to generate coherent electromagnetic radiation across the UV and x-ray ranges. Electrical charges are forced to oscillate in an electromagnetic field of period L and emit electromagnetic (e.m.) radiation due to acceleration (bremstrahlung). Propagation of e.m. radiation generated at one oscillation yields stimulated emission at next oscillation, i.e., coherent superposition of e.m. waves occurs, leading to emission of monoenergetic, coherent, collimated and intense radiation (Fig. 1). This is the working principle of the free electron laser (FEL) [1], whose operation has been experimentally demonstrated at some laboratories worldwide down to $L \cong 1$ cm. The spectrum of e.m. radiation peaks approximately at the frequency $\upsilon = 2c\gamma^2/L$, where c is the light speed and γ the relativistic factor [2]. In modern accelerators γ is of the order of 10^3.

Channeling is the confinement of positively charged particles in the electromagnetic field of a crystalline lattice [3]. Channeling occurs as the particle's momentum is nearly parallel to a crystalline plane (planar channeling) or major lattice direction (axial channeling). Thereby, a periodically undulated crystal would create a preferential pathway for positively-charged particles under channeling condition (Fig. 1).

Undulation radiation (UR) is the result of charge oscillations in the crystal [4–6], whose period lies in the millimetric or sub-millimetric range, i.e., a periodicity which is not currently accessible to FEL. Preliminary indication of the achievement of UR has been recently reported [7] though the search for clearer experimental evidences is still under investigation [8].

Various methods have been proposed to realize a crystalline undulator (CU), many of which are summarized in Ref. [9]. As suggested in Ref. [10], a promising technique for the realization of a CU takes advantage of modern technology in microelectronics, about patterning of a silicon substrate with deposition of a thin layer of insulator onto its surface. Indeed, an

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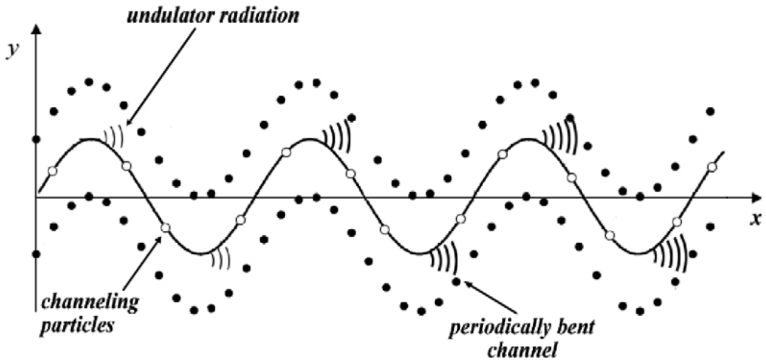

Fig. 1. Trajectory of a charged particle confined inside a periodically deformed crystalline lattice. Dimensions along x and y axes are not scaled.

alternate series of thin tensile strips deposited on both sides of a silicon wafer and perpendicularly to the nominal trajectory of charged particles, would generate a periodic deformation field. Channeling of particles in a periodically deformed lattice guarantees oscillations and, in turn, e.m. radiation emission. An investigation to show that the proposed method matches the requirements for UR emission has recently appeared in the literature [9].

CU may be used to generate hard x-ray radiation, whose properties are fundamental to high-resolution crystallography. Such technique will allow precise determination of reaction mechanism of most biological systems, a knowledge which is poorly accessible with currently available techniques.

Although rather a clear understanding of the physical processes involved in the fabrication of a CU does exist, the need for an engineering investigation is required with the aim to aid further development and to implement future fabrication of the device.

In the present work a linear elastic behaviour under small strains is adopted to describe the mechanical behaviour of a CU since that very small deformations are imparted to the silicon substrate in order to realize this kind of structures. Nonetheless, it should be remarked that assumption of infinitesimal strains does not necessarily imply a liner relationship between strains and stresses, as reported in [11]. Therefore, a linearized elastic model has been assumed as a reasonable approximation of the actual behaviour of the structure with the aim to propose simple and useful analytical models utilizable for the design of the device. The model in question is an approximated model and the same experimental results could in fact be interpreted within the context of more general models. Finally, the extension of the present study to the finite strains and to nonlinear elastic constitutive relationships could be an interesting approach for the design of CUs.

The paper is organized as follows. The main aspects of the object of study and the description of the problem are given in Section 2; subsequently, a brief description of the procedure performed to realize the undulator is briefly given in Section 2.1. The choice of the mechanical parameters employed in the numerical simulations is discussed in Section 2.2, whereas the assumptions concerning the mechanical models are presented in Section 2.3; in this section the principal results obtained from the numerical analysis are also compared with theoretical and experimental data in order to validate the finite element model employed. In Section 3 the results of the numerical simulations of the undulator are reported. In order to evaluate the deformation of the structure at hand, silicon substrate can be modelled like an isotropic material without appreciable errors: this is showed in Section 3.1. To assess the effects of the design parameters on the mechanical behaviour of the undulator, a sensitivity study is performed in Section 3.2; next, a simplified method utilizable to predict average amplitude of the periodic undulation is proposed in Section 3.3. Local effects, such as stress concentrations, are also evaluated with an analytical formulation proposed by one of the authors in Section 3.4 and compared with numerical solutions.

2. Description of the problem

The object of the present study is the mechanical behaviour of a crystalline undulator (CU) with sub-millimetric period, obtained patterning the surface of a plane silicon (Si) lamina with strips in silicon nitride (Si_3N_4). The alternate strips (Fig. 2) are applied on the substrate in order to obtain a periodic undulation of the lamina.

At the Sensors and Semiconductors laboratory of the University of Ferrara, crystalline silicon undulators having various substrate thickness have been realized through LPCVD method (see Section 2.2) applied to circular silicon wafers [10]. Previous experiences revealed that 200 μm is a convenient value of the substrate thickness in order to obtain appropriate values of deformation amplitudes and radii of curvature suitable to realizing a CU with sub-millimetric undulation. Thus, in the present study, h_s is assumed equal to 200 μm.

In order to obtain a sub-millimetric periodicity of the deformation, strips width a and strips spacing p are assumed in the range 100–500 μm. Accordingly, the value of film thickness h_f is of the order of 100–1000 nm.

To avoid de-channeling of particles [12], previous experience suggests to assume the length l of the undulator equals to some millimetres; moreover, the width w of the undulator is dictated by sake of practice to be equal to few centimetres.

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