Authentication of integrated circuits in the THz domain using diffraction grating structure on silicon substrate

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Authentication of integrated circuits in the THz domain using diffraction grating structure on silicon substrate

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In this paper, we propose a method to authenticate integrated circuits (ICs) using a diffraction grating engraved on the backside of their silicon substrate and which could be embedded within the packaging. The geometrical dimensions of the grating are chosen to lead to the assisted coupling of terahertz (THz) waves within the silicon substrate that acts as a waveguide. When considering the reflected (or transmitted) THz signal by the engraved substrate, the coupled THz modes are missing and their characteristics depend closely on the dimensions of the grooves and the permittivity of the materials. The very high sensitivity of the THz signature of the device to these parameters can be used for authentication of ICs.

Introduction: Counterfeiting of electronics components are growing long-standing problems, which affect the whole supply chain of the distributors, causing a loss of \$100B [1] and serious risk incurred with the millions of users of these chips. Nowadays, authentication of integrated circuits (ICs) can be achieved using Physical Unclonable Function (PUF) [2] technology that consists in a specific and theoretically unpredictable function implemented during the ICs fabrication process. In the THz domain, exploratory contactless techniques were already published for quality control [3] and more recently for counterfeit detection of electronic components [4]. This latter showed the capability of ICs authentication using THz imaging taking benefit of the moderated absorption of the packaging materials. Nevertheless, the performances of the THz imaging, more particularly in terms of spatial resolution, are limited by the diffraction limit to a few hundred micrometers. In the present work, we propose a new approach based on the use of the spectral signature of diffraction gratings engraved on the backside of the ICs to be authenticated. These periodic grooves, whose depth of several tens of micrometers, can be obtained using diamond saw or chemical etching [5]. The etched substrate acts as a dielectric waveguide associated to a 1D diffraction grating [6]. When the coupling conditions are verified, the reflected and transmitted THz spectra exhibit absorption lines (m-lines) that can be used as a broadband and rich spectral signature. For a given incident angle, the number of m-lines, their frequency positions and depth depend on the geometrical dimensions of the structure. Consequently a unique etching scheme leads to a unique spectral response. The simulated results presented in this paper show that very small changes of geometrical parameters of the grating (period and/or etching depth) in comparison to the THz wavelengths, lead to noticeable variation of the spectral response reflected by the structure, which can be therefore authenticated.

Structure and method principle: The simulated structure is presented in Fig. 1. It is constituted of a 1D rectangular diffraction grating engraved on the backside of the high resistivity silicon substrate of the IC to be authenticated. A top layer has been considered to represent the deepest electronics layers of the IC and processed with different materials, *e.g.* silicon oxide or semiconductors. To simulate such a structure, we used a software based on the differential method [7]. Because of the software limits, the metal patterns have not been taken into account in this study but will not fundamentally change the conclusion of this letter. In this study, the geometrical parameters of the grating have been initially chosen to match with the microelectronic standards and etching techniques [5]: the wafer thickness $e_1 = 775$µm (thickness of 11.8-inches silicon wafer). In the considered frequency range from 100 GHz to 1 THz, the complex permittivity of air and silicon are respectively $\varepsilon_{air} = 1$ and $\varepsilon_{si} = 11.62 + j\ 5.10^{-5}$ (silicon resistivity > 1000 Ω.cm^{-1}). In this structure, considered as the reference one, the thickness of the top layer $e_{TL} = 50$ nm and the permittivity $\varepsilon_{TL} = 4.5 + j\ 0.07$ corresponds to SiO_2 material [8], that is typically used as a passivation layer. The period of the grating $\Gamma = 250$ µm, the grooves depth $p = 80$ µm that mainly impacts the coupling efficiency [6, 9], and the incident angle $\theta = 10°$ were chosen to obtain a sufficient number of m-lines in the reflected signature. The frequency resolution is set to 2.3 GHz, corresponding to the one typically reached in THz TDS setup.

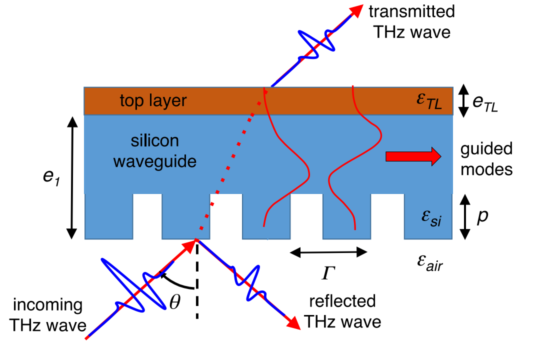

Fig. 1 *Transversal scheme of the proposed structure dedicated to ICs authentication.*

We plot in Fig. 2 the modulus of the reflection coefficient of the previously described structure. We can first notice some oscillations due to Fabry-Pérot effect in the whole structure, whereas a large number of m-lines corresponding to the coupled guided modes, are superimposed (arrows refer to some principal m-lines). These peaks are at the origin of the information richness of the THz signature. Note that the reflected configuration has been chosen to address authentication of ICs whose metallization levels can prevent any precise THz measurements in transmission. Nevertheless, similar results can be obtained in transmission regarding the intended application.

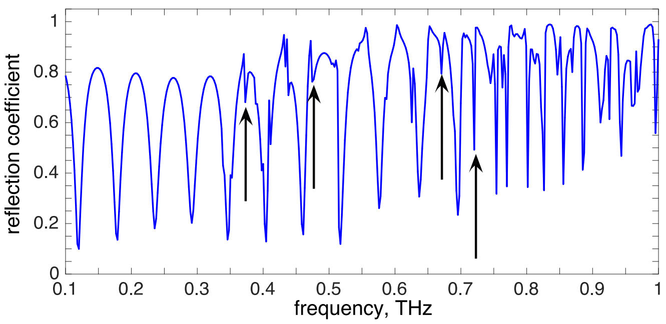

Fig. 2 *THz spectral signatures (modulus of the reflection coefficient) of the 775 µm air-silicon device with 50 nm top layer made of* SiO_2.

Results: To point out the sensitivity of the reflected THz signature relatively to the geometrical parameters, we simulate the reflection of structures that geometrically differ from the reference one. Their so-obtained reflection moduli are then compared to the reference signature (Fig. 2), by calculating correlation coefficients (CCs) over the frequency range from 100 GHz to 1 THz. In order to increase the discriminative power of the method, the CCs are also calculated from the 1st and 2nd derivatives of the spectral signatures. Fig. 3.a exhibits the evolution of the CCs when only the grating period Γ varies of ± 5 µm in comparison to the actual value ($\Gamma = 250$ µm), while Fig. 3.b shows the impact of grooves depth change ($p = 80 \pm 20$µm). According to Fig. 3, CCs calculated from signatures significantly drop when Γ and p vary only of a few µm, showing it is possible to discriminate two close structures by comparing their THz signatures. For both geometrical parameters, the discrimination is getting even more obvious when considering the 1st or the 2nd derivative of the reflection modulus, since CCs reach roughly 0 (*i.e.* they have no similarities) for geometrical variations as small as a few µm. Indeed, derivation of the reflected THz signals lead to an exacerbation of the narrow resonances (*i.e.* m-lines) and a smooth of the broadest ones (*i.e.* Fabry-Pérot oscillations). Therefore, as Γ rules the frequency positions of m-lines and p the coupling efficiency, CCs calculated from the derivatives of the THz signature are more sensitive to the Γ variation. Hence, Γ and p can be simultaneously and finely tuned to generate a significant number of reflected THz signatures, all simply discriminated each other, by calculating the CCs on their 2nd derivatives; this latter will be referenced as the "authenticator" thereafter.

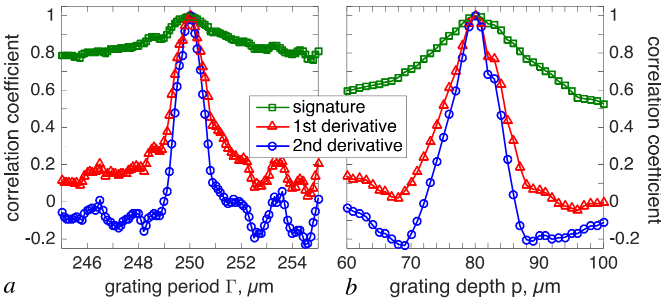

Fig. 3 *CCs versus a) the grating period Γ, and b) the grating depth p. CCs are calculated from the reflection coefficient and from its 1st (triangles) and 2nd (circles) derivatives (θ =10°, e_1=775 μm, e_{TL}=50 nm).*

Let's now pay attention to the influence of some constituent parameters of the ICs, related for example to the architecture and the manufacturing process of the ICs to be authenticated. In this study, we focus on the impact of the substrate thickness e_1, the top layer permittivity ε_{TL} and thickness e_{TL}. Fig. 4.a exhibits the CC of the second derivative of the reflected signature versus the variation of the wafer thickness e_1. Results show that two identical ICs (same function, architecture and process) can be discriminated as long as they are fabricated on silicon substrates whose thicknesses differ each other of only a few microns. Taking into account the thickness accuracy provided by the substrate manufacturer (typically $\Delta e_1 = \pm$ 25 μm), this means that the method is potentially able to distinguish two series of ICs fabricated on two different silicon wafers.

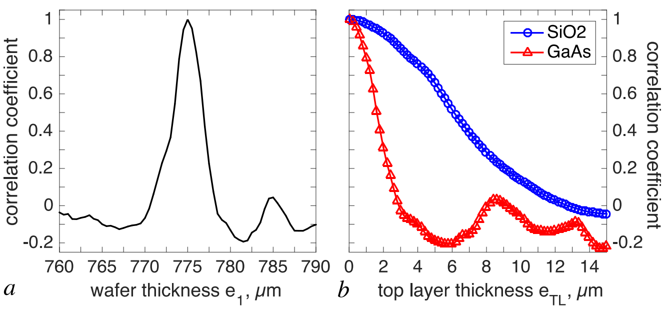

Fig. 4 *CCs calculated from the 2nd derivatives of THz signatures versus (a) the wafer thickness, and (b) the effective thickness of the top layer.*

In order to highlight the impact of active layers in the authenticator behaviour, we take into account two simple cases of constituent materials for the top layer: SiO_2 and GaAs. This layer is also assumed to be homogeneous. Let's precise that contrary to the reference device, the top layer refers now to the actives layers and not to the native oxide on the silicon wafer. Moreover, and because of the THz wavelengths, the authenticator is not notably influenced by the presence of the nanometric thin layer like native oxide [10]. Fig. 4.b shows the authenticator sensitivity to the top layer thickness, *i.e.* the sensitivity of the guided modes to the penetration depth of their evanescent field in this layer. First and as expected, the authenticator is largely influenced by the thickness of the top layer since the CCs steeply drop down when it varies of a few micrometers, whathever is the material of interest. We also notice that this drop is more abrupt in case of GaAs compared to SiO_2, phenomena that can be anticipated as the real part of the permittivity of GaAs [11] (12.96) is of the order of the silicon one (11.62), wheheras for the oxide it is smaller around 4.5. In case of a SiO_2 layer on Si substrate, the permittivity step is larger and leads to a larger confinement of the THz guided modes, and in turn to a smallest penetration depth of the evanescent mode. This leads finally to a less sensitivity of the authenticator to the top layer. More generally, all the active layers constituting the top layer, which are probed by the THz evanescent field can be seen in first approximation to a homogeneous single layer with effective thickness e_{TL} and of permittivity ε_{TL}. Therefore, the two curves presented in fig. 4b are limits of practical cases, since these layers are mostly composed of dielectrics and semiconductors materials. We can then expect that the practical cases will be comprised between the two curves presented in Fig. 4.b. Finaly and to quantitatively illustrate the sensitivity of the method proposed in this letter, we can arbitrarly consider a decision threshold of 0.2 below which the authenticator is verified. Such threshold is achieved as soon as the variations of the geometrical parameters reach the following values: $\Delta\Gamma$ = 0.8 μm, Δp = 6 μm , Δe_1 = 3 μm and e_{TL} = 2.4-9 μm depending of the top layer permittivity ε_{TL}.

Conclusion: We demonstrated the possibility to authenticate ICs in the THz frequency range using a diffractive grating structure directly engraved on the backside of the device. We show that the correlation coefficient applied to the second derivative of the reflected THz signature of the grating can be used as an extremly sensitive authenticator. Such an authenticator leads to discrimination of close structures whose geometric properties differ of a few micrometers from the other. These variations can be deliberately induced during the design or simply and randomly due to the inaccuracies of the manufacturing methods. Finally, to increase the robustness of this method against counterfeiting, the diffracting device can be buried into the packaging material: the grating becomes then out of sight. Such a struture can be also associated with already used techniques like PUF for example [2].

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