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SUMMARY

Detection of hidden gratings using light and sound

The ambition to stay in trajectory with Moore's Law has pushed the semiconductor industry to introduce a radical new design of memory chips called "3D-NAND" memory. During the fabrication of "3D-NAND" memory, it is often necessary to optically detect the presence of micro/nano structures buried underneath many dielectric and metallic layers. An example of suc a buried structure is a so-called alignment grating, which is a grating etched in Si. When light is diffracted off such a grating, a small change in position of the wafer changes the phase difference between the -1^{st} and $+1^{\text{st}}$ order diffracted light beams, which can be used to determine the position of the wafer with sub-nanometer accuracy. However, when optically opaque dielectric and metallic layers are deposited on top of these gratings, it becomes impossible to detect them using visible/IR light. Fortunately, materials that are opaque to visible/IR light are often transparent to sound.

In this thesis, the use of laser-induced ultrasound waves is proposed to detect hidden alignment gratings. We fabricated metal gratings on top of flat layers of metal/dielectric layers on a glass substrate and performed pump-probe experiments from the substrate side. Hence, both the 400 nm pump pulse and the 800 nm probe pulse see a nominally flat surface, and the grating is effectively optically hidden. The femtosecond pump pulse generates an acoustic wave in the metal layer that propagates through the metal/dielectric layers and reflects off the buried grating. The acoustic wavefront returning to the metal-glass interface now has a shape resembling that of the buried grating. This gives rise to a 'grating-shaped' deformation of the metal-glass interface. A delayed probe pulse diffracts from this imprinted grating, and the diffracted signal is observed. The observation of a diffraction signal indicates that we can detect the presence of a buried grating using the pump-probe technique.

The results of this thesis can be divided into three parts. The first part, consisting of Chapters 4 and 5, focuses on the generation of acoustic waves. The first step in the generation of extremely-high frequency acoustic waves is the absorption of light by the free-electron gas. The subsequent thermalization, cooling of the electron gas together with the electron energy diffusion, are essential ingredients to determine where the absorbed laser energy is transformed into lattice heat. In Chapter 4, measurements and calculations of electron dynamics in single metallic layers and in metallic bilayer upon excitation with a femtosecond laser pulse are shown. It was observed that the electron dynamics is strongly influenced by the thickness of the metal and by the strength of the electron-phonon coupling. These effects were then used to determine the presence and nature of a metal grating buried below an optically opaque gold layer. In Chapter 5, the measurements and calculations of transient-grating pump-probe experiments on flat metal layers are discussed. It was shown that it is possible to launch a grating-shaped acoustic wave in flat metal layers by means of transient-grating pump pulses, and that a probe pulse can diffract from the grating-shaped acoustic wave.

The second part of this thesis primarily focuses on the propagation of acoustic waves through metals and dielectrics, and the ability of laser-induced ultrasound to detect gratings buried below multilayers. It was shown in Chapter 6 that the high-frequency acoustic wave can propagate through a stack of tens of 18 nm thick SiO_2 and Si_3N_4 layers, reflect off the buried grating, and give rise to probe pulse diffraction from the grating-shaped acoustic echo. The shape and strength of the time-dependent diffraction signal can be accurately predicted using an elaborate numerical model. The diffracted signal strength is not strongly influenced by the number of dielectric layers through which the acoustic wave has to propagate, and the acoustic wave “sees” the SiO_2 and Si_3N_4 stack as an equivalent time-averaged acoustic medium.

The third and final part focuses on the detection of acoustic waves, and the limits of the photoacoustic technique are explored. In Chapter 7, pump-probe measurements on samples with buried gratings with amplitudes as small as 1 nm are shown. It was observed that probe light scattering from interface roughness constructively or destructively interferes with the light diffracted from the grating-shaped acoustic echoes. This drastically affects the shape and strength of the time-dependent diffracted signal. The intensity of the scattered light was quantified using Rayleigh-Rice scattering theory and later used to simulate the shape of the diffracted signals.

I have shown that pump-probe laser-induced ultrasound shows promise as a new, non-contact, all-optical grating detection- and imaging-modality for wafer alignment applications by using ultrasound to make an acoustic copy of the buried grating, while using conventional optical diffraction to read-out the copy when it reaches the surface.

SAMENVATTING

Verborgen uitlijntralies meten met licht en geluid

The ambitie om Moore's Law voort te zetten heeft in de halfgeleiderindustrie geleid tot het introduceren van een radicaal nieuw type flashgeheugen, genaamd '3D-NAND'. Tijdens de fabricage van een "3D-NAND" geheugenchip is het vaak nodig om op optische wijze micro/nano structuren te detecteren. Deze structuren zijn vaak bedekt met meerdere lagen van een diëlektricum of een metaallaag. Een voorbeeld van zo'n bedekte structuur is een zogeheten uitlijntralie geëtst in een Si wafer. Als een lichtbundel dit tralie belicht zal een kleine verandering in de positie van de wafer een verandering van het optische faseverschil tussen de -1^e en +1^e orde diffractiebundels tot gevolg hebben. Deze verandering van het faseverschil kan gebruikt worden om de positie van de wafer te bepalen met sub-nanometer precisie. Echter, wanneer ondoorzichtige lagen van een metaal of een diëlektricum op dit uitlijntralie worden gedeponeerd, wordt het onmogelijk om deze te detecteren met zichtbaar/IR licht. Gelukkig zijn materialen die onzichtbaar zijn voor zichtbaar/IR licht vaak transparant voor geluidsgolven. In dit proefschrift wordt het gebruik van laser-geïnduceerde ultrasone geluidsgolven voorgesteld als methode voor het detecteren van verborgen uitlijntralies. Om dit te testen hebben we metalen tralies gefabriceerd bovenop vlakke lagen van een metaal en diëlektrica op een substraat van glas. Vervolgens hebben we 'pomp-probe' experimenten uitgevoerd vanaf de substraatkant. In deze configuratie 'zien' zowel de 400 nm pomppuls als de 800 nm probepuls een vlak oppervlak en is het tralie optisch verborgen. De femtoseconde pomppuls lanceert een geluidsgolf in de metaallaag die zich voortplant door het metaal en de diëlektrische lagen. Aangekomen bij het verborgen tralie zal de geluidsgolf reflecteren en terugkeren naar het glazen substraat. Het golffront van de gereflecteerde geluidsgolf heeft na reflectie een vorm vergelijkbaar met dat van het tralie. Wanneer deze geluidsgolf het grensvlak tussen de metaallaag en het glazen substraat bereikt, zal het deze daardoor verstoren met een zelfde ruimtelijke periode. Deze modificatie van het grensvlak functioneert vervolgens zelf als een tralie voor een vertraagde probepuls die dit tralie belicht. De diffractie van de probepuls aan dit tralie kan vervolgens worden gedetecteerd en markeert de aanwezigheid van het oorspronkelijke verborgen tralie. De resultaten beschreven in dit proefschrift kunnen worden onderverdeeld in drie delen. Deel één omvat Hoofdstuk 4 en 5, en focust op het genereren van geluidsgolven. De eerste stap in de generatie van geluidsgolven met extreem hoge frequenties is de absorptie van lichtpulsen door het vrije-elektronengas. Een beschrijving van de daarop volgende thermalisatie, d.w.z. het afkoelen van het elektronengas en de elektronenergiediffusie, is essentieel om te achterhalen waar de geabsorbeerde laser energy overgaat in opwarming van het atoomrooster. In Hoofdstuk 4 word de elektrondynamica, die plaatsvindt na excitatie door een femtoseconde laserpuls, voor zowel een enkele als een dubbele metaallaag, beschreven door middel van metingen en berekeningen. We constateren dat de elektrondynamica sterk afhangt van de dikte van de metaallaag en van de koppeling tussen de elektronen en de fononen. Aansluitend wordt deze kennis gebruikt om de aanwezigheid en het karakter van een metalen tralie, bedekt onder een ondoorzichtbare laag goud, te bepalen. In Hoofdstuk 5 worden metingen en berekeningen aan transiente-tralies in pomp-probe experimenten, behandeld. In deze experimenten wordt een geluidsgolf met de vorm van een tralie gelanceerd in vlakke metaallagen door gebruik te maken van twee, onder een hoek interfererende, pomppulsen. Er word aangetoond dat een probepuls diffracteert aan de tralies veroorzaakt door meerdere akoestische echo's die terugkeren naar het oppervlak. Het tweede deel van dit proefschrift gaat voornamelijk over de voortplanting van geluidsgolven door metalen en diëlektrica, en het detecteren van tralies bedekt onder meerdere lagen, gebruik makend van ultrasone geluidsgolven. In Hoofdstuk 6 word aangetoond dat een hoogfrequente geluidsgolf zich kan voortplanten door enkele tientallen lagen SiO_2 en Si_3N_4 van 18 nm dik, vervolgens reflecteert aan het bedekte tralie, en als tralie-vormige echo diffractie van een probepuls kan veroorzaken. De vorm en intensiteit van het tijdsafhankelijke diffractiesignaal kan nauwkeurig worden voorspeld door een uitgebreid numeriek model. De intensiteit van het diffractiesignaal is niet sterk afhankelijk van het aantal diëlectrische lagen waar de geluidsgolf zich door voortplant. Verder blijkt dat de gestapelde SiO_2 en Si_3N_4 lagen kunnen worden beschreven als een enkele laag met een effectieve dikte en met materiaal eigenschappen die tussen die van SiO_2 en Si_3N_4 inliggen. Het derde en laatste deel behandelt de detectie van geluidsgolven en verkent de limieten van de fotoakoestische techniek. In Hoofdstuk 7 worden pomp-probe metingen beschreven aan bedekte tralies met amplitudes in de orde van een enkele nanometer. We hebben gevonden dat probe licht dat verstrooit aan grensvlakoneffenheden, constructief of destructief kan interfereren met de diffractie afkomstig van de tralie-vormige geluidsgolf. Dit heeft een sterke verandering van de vorm en intensiteit van het tijdsafhankelijke diffractiesignaal tot gevolg. De intensiteit van het verstrooide licht kan gekwantificeerd worden met behulp van de Rayleigh-Rice theorie en naderhand worden gebruikt om de vorm van het diffractiesignaal te simuleren. Ik heb laten zien dat pomp-probe, laser-geïnduceerd ultrageluid potentie heeft als een nieuwe, contactloze en volledig optische tralie-detectie- en afbeeld-modaliteit voor waferuitlijnapplicaties. Met behulp van ultrageluid wordt een akoestische kopie van het verborgen tralie gemaakt welke, wanneer deze het oppervlak bereikt, vervolgens wordt gedetecteerd met conventionele optische diffractie.

PUBLICATIONS

THIS THESIS IS BASED ON THE FOLLOWING PUBLICATIONS:

1. **S. Edward**, A. Antoncecchi, H. Zhang, H. Sielcken, S. Witte, and P. C. M. Planken, "Detection of periodic structures through opaque metal layers by optical measurements of ultrafast electron dynamics," Opt. Express **26**, 23380–23396 (2018) (**Chapter 4**).
2. H. Zhang, A. Antoncecchi, **S. Edward**, I. Setija, P. Planken, and S. Witte, "Unraveling phononic, optoacoustic, and mechanical properties of metals with light-driven hypersound," Phys. Rev. Appl. **13**, 014010 (2020) (**Chapter 5**).
3. **S. Edward**, H. Zhang, I. Setija, V. Verrina, A. Antoncecchi, S. Witte, and P. Planken, "Detection of hidden gratings through multilayer nanostructures using light and sound," Accepted in Phys. Rev. Appl. (2020) (**Chapter 6**).
4. **S. Edward**, H. Zhang, S. Witte, and P. Planken, "Role of surface roughness in photoacoustic detection of low amplitude buried grating," Under review (**Chapter 7**).

THE AUTHOR CONTRIBUTED TO THE FOLLOWING PUBLICATIONS:

1 **S. Edward**, et al. and P. Planken, “ Photoacoustics, thermal transport and electron dyanmics in thin film Ru,” In Preparation.

2 V. Verrina, **S. Edward**, H. Zhang, A. Antoncecchi, S. Witte, and P. Planken, “Role of scattering by surface roughness in the photoacoustic detection of hidden micro-structures,” Under review.

3 V. Verrina, **S. Edward**, H. Zhang, S. Witte, and P. Planken “Photo acoustic detection of low duty-cycle gratings through optically opaque layers,” Under review.

4 A. Antoncecchi, H. Zhang, **S. Edward**, V. Verrina, P. Planken, and S. Witte, “Scanning pump-probe for sub-surface microscopy,” Under review.

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