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Precision 3-D Surface Measurement of Step-structures Using Mode-locked Femtosecond Pulses

Young-Jin Kim,[1,2,*] Minah Choi,[1] Keunwoo Lee,[1] Heesuk Jang,[1] Jiyong Park,[1] and Seung-Woo Kim[1,*]

[1]Department of Mechanical Engineering, Korea Advanced Institute of Science and Technology (KAIST), Science Town, Daejeon, 305-701, Republic of Korea
[2]School of Mechanical & Aerospace Engineering, Nanyang Technological University (NTU), 50 Nanyang Avenue, 639798, Singapore

ABSTRACT

Fast, precise 3-D measurement of step-structures fabricated on microelectronic products is essential for quality assurance of semiconductor, flat panel display and photovoltaic products. Optical interferometers have long been used, but not that wide-spread for step-structures due to their phase ambiguity or low spatial coherence. Femtosecond pulse lasers can provide novel possibilities to optical profilometry both in the time and the frequency domain. In the time domain, step-surfaces can be measured over wide area by exploiting low temporal but high spatial coherence of femtosecond pulses; in the frequency domain, multi-wavelength interferometry permits the absolute measurement over the discontinued surface profiles while maintaining the sub-wavelength measurement precision.

Keywords: Precision measurement, femtosecond laser, optical interferometry

1. INTRODUCTION

Microelectronic packaging is gaining more attention as customers' demands for faster, smaller, lighter, thinner, and high performance electronic products grow rapidly. Discontinuous microelectronic step-structures are also essential for flat panel displays and photovoltaic products [1], but impose challenges in measuring the step height precisely in a fast way for quality assurance during manufacture. Conventional interferometric profilers using monochromatic lasers are not suitable for profiling discontinuous surface features due to the 2π phase ambiguity [2]. There are two possible solutions; the first one is using well-defined multiple monochromatic wavelengths to increase the non-ambiguity range (NAR) to be wider than the target step-heights and the other one is using low-coherence interferometry which inherently generates low-coherence interferogram within a limited coherence range less than several tens of micrometers. Interestingly, femtosecond pulse lasers enable us to approach both directions: low-coherence interferometry in the time domain and multi-wavelength interferometry in the frequency domain. In this investigation, large-stepped discontinuous surface structures were precisely measured using time- and frequency-domain characteristics of the femtosecond pulse laser.

2. LOW-COHERENCE INTERFEROMETRY USING FEMTOSECOND LASER PULSES IN THE TIME DOMAIN

Low-coherence interferometry relying on broadband light sources are free from the phase ambiguity in principle, as interferometric fringes can be produced within a narrow range only when the optical path difference (OPD) approaches zero [3]. Despite the advantage, the low spatial coherence of broadband sources restricts the lateral field-of-view (FOV) usually to several square millimeters, while the interferometer design is required to be strictly symmetric and equal-path between the measurement and reference arms [4]. Furthermore, it is not easy to improve the vertical scanning speed and range due to the practical limitations of micro-actuators available today. We demonstrated a fast and precise profiling

*yj.kim@kaist.ac.kr; *swk@kaist.ac.kr;

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method of microelectronic step-structures by low-coherence scanning interferometry using femtosecond laser pulses. An unequal-path, non-symmetric interferometer system is configured such that the OPD between the reference and measurement arms are varied by scanning the repetition rate of femtosecond pulses. Furthermore, the high spatial coherence of femtosecond pulses provides higher visibility over a wide FOV [5].

Figure 1 shows the low-coherence interferometer configured in this investigation. An Er-doped fiber femtosecond laser is used as the light source to generate femtosecond pulse train at a repetition rate of 100 MHz. The generated pulse train is divided into two interferometer arms; one is the reference arm of a long length made of a single-mode fiber and a dispersion compensation fiber. The other is the measurement arm of a short length of only a single-mode fiber. The center wavelength of the original pulses is halved to 780 nm at a PPLN so that the resulting interferometric fringes can be monitored with a conventional visible CCD. The repetition rate is scanned precisely with reference to the Rb atomic clock by elongating the cavity length of the laser oscillator. Then the unbalanced optical delay of the unequal-path configuration converts the variation of f_r to the OPD scanning as illustrated in Fig. 2. Three different f_r-scanning mechanisms with different tuning ranges and speeds are employed in series: an EOM, a PZT and a motorized stage. When converted to actual OPD variation, the tuning range and speed by each scanning mechanism are magnified as a function of the unbalanced length of the interferometer.

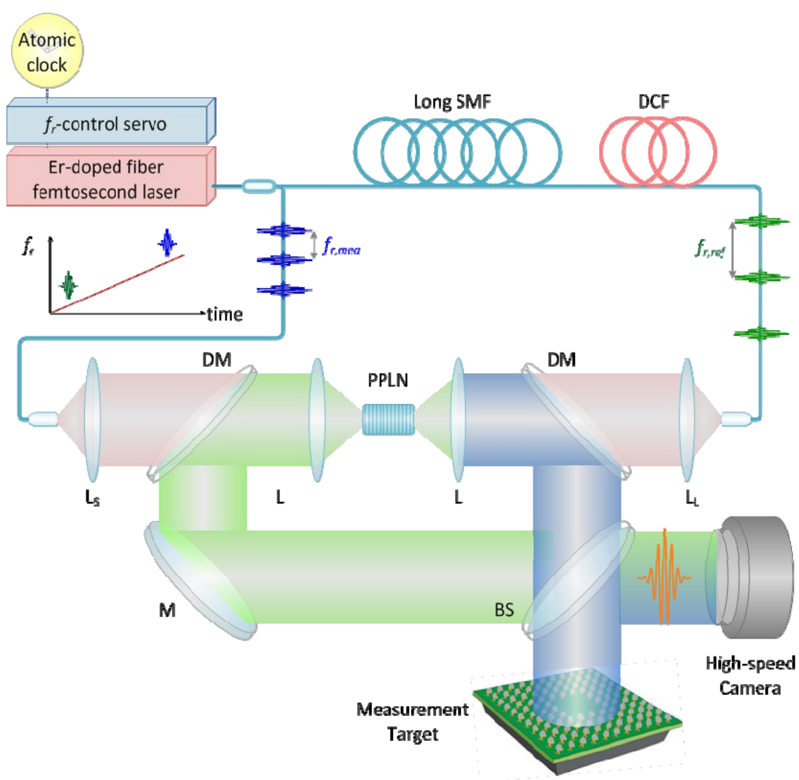

Figure 1. Low-coherence scanning interferometer using femtosecond pulses in the time domain for 3-D profilometry of microelectronic step-structures. Abbreviations are; SMF: single-mode fiber, DCF: dispersion compensating fiber, DM: dichroic mirror, PPLN: periodically poled lithium niobate.

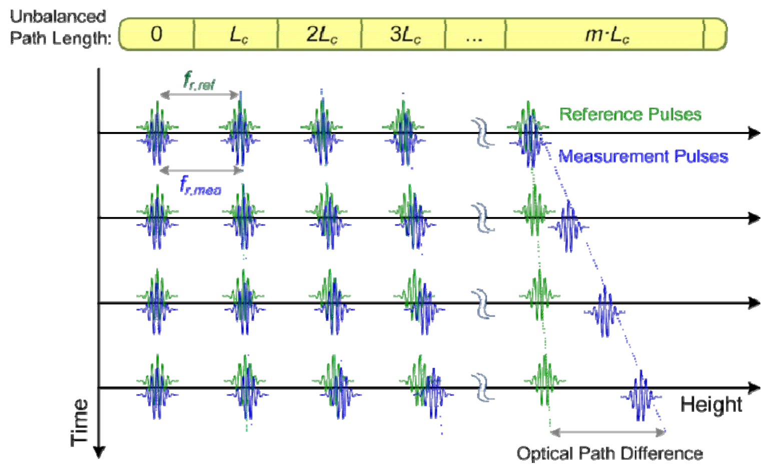

Figure 2. Conceptual diagram of relative scanning effect between the reference and measurement pulses at unequal-path interferometry.

A standard step-height of 69.6 μm was measured to demonstrate the measurement capability. Profiling high step-structures requires a large OPD scanning range; f_r was tuned from 99.37902000 to 99.37942000 MHz with an increment of 0.04 Hz, which corresponds to 60 nm scan step. The number of digits of the repetition rate presents the high scanning precision realized in the measurement. The 3D profile map was reconstructed as shown in Fig. 3. The repeatability was evaluated by repeating 15 measurements over five sample bumps to 45.1 nm with centroid algorithm. This confirms that the proposed system is capable of measuring high step-structures such as metal bumps, through-silicon-vias, and column spacers used in microelectronic products.

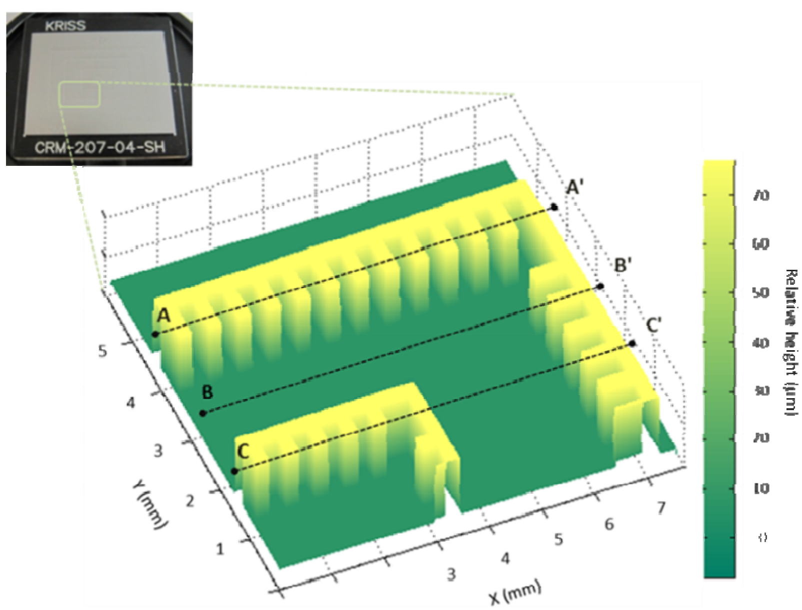

Figure 3. Measurement of high step-structures by low-coherence interferometer. Reconstructed 3-D profile showing step heights of ~69.6 μm.

3. FREQUENCY-COMB-REFERENCE MULTI-WAVELENGTH INTERFEROMETRY IN THE FREQUENCY DOMAIN

We also demonstrated a multi-wavelength interferometer which enables determination of large surface step heights by use of four different wavelengths that are referenced to the frequency comb of a femtosecond laser. This frequency-comb-based method is fast and capable of maintaining sub-wavelength precision with direct traceability to the Rb clock [6,7], being well suited for not only standard metrology but also industrial applications. Figure 4 shows the system layout of the multi-wavelength interferometer for measurement of largely stepped surface profiles. The light source is an Er-doped fiber laser with a 50 nm bandwidth centred at a 1550 nm wavelength. The frequency comb of the fiber laser is stabilized to the Rb atomic clock of 10^{-12} uncertainty. Then, four cw distributed feedback lasers (DFB) are phase-locked to the four individual frequencies selected from the frequency comb [8]. A 4×1 fiber switch is used to route the phase-locked four DFB lasers, one by one sequentially, to the interferometer through a second harmonic generation (SHG) crystal. The output frequencies of the DFB lasers are consequently doubled to the near-infrared range about 775 nm which is well observed by the CCD camera with high sensitivity. The interferometer is of Twyman-Green type whose field-of-view is extended to cover a wide imaging area. The reference mirror is a flat of ~λ/10 wavefront error, while the target specimen is comprised of large-step structures. The reference mirror is translated by 100 nm using the PZT for phase-shifting along the optical axis.

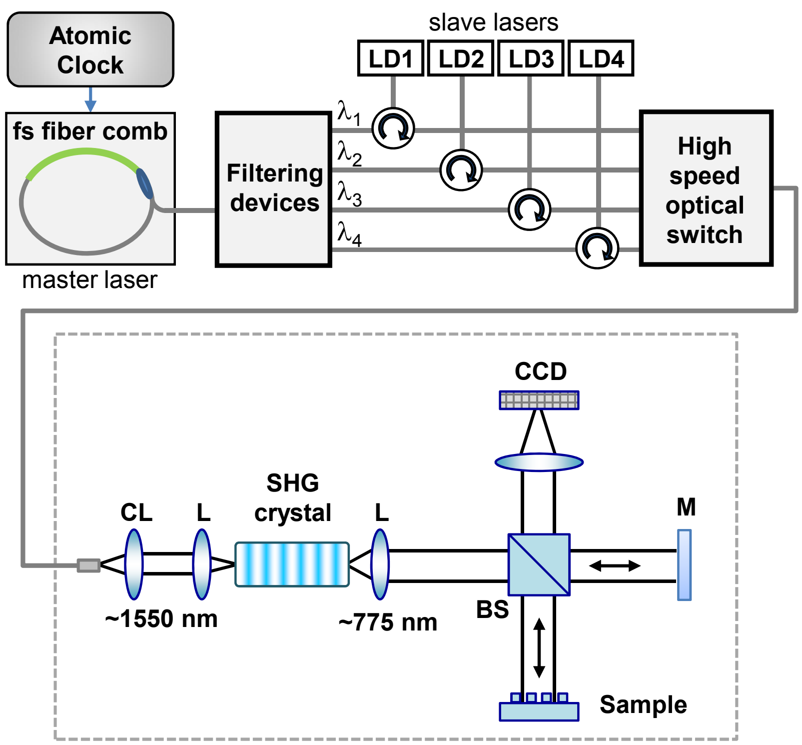

Figure 4. Frequency-comb-referenced multi-wavelength interferometer for large step-height measurement.

Multi-wavelength interferometry permits overcoming the 2π phase ambiguity of single-wavelength interferometry by use of well-defined multiple wavelengths [9,10]. For a single wavelength λ, the surface height h is expressed as $h = \lambda(m+e)/2$, in which m is a positive integer and e denotes the excess fraction ($1>e\geq 0$). The value of e is directly determined from the measured interferometric phase, but the integer m is not. Thus, using multiple wavelengths (for example, four wavelengths), the surface height is given in the form of simultaneous equations as,

$$h(x,y) = \frac{\lambda_i}{2}\left[m_i(x,y) + e_i(x,y)\right] \quad (1)$$

where i = 1, 2, 3, 4. The number of unknowns (m_1, m_2, …, m_N, and h) is always one larger than that of the given equations. Thus, the positive integers mi have to be determined within a non-ambiguity range by numerical means [11]. The non-ambiguity range is determined by the number of the wavelengths in use and their uncertainty. Our comb-based method of multi-wavelength generation can provide any desired set of wavelengths within the spectral bandwidth of a femtosecond laser. With carefully selected four wavelengths, the non-ambiguous range can be largely extended up to tens of millimeters.

Absolute surface profile of a standard specimen with a 70 μm step-height was measured using this interferometer. The specimen prepared by e-beam lithography is comprised of rectangular flat bumps with high aspect ratio. The field-of-view of measurement was 8.7 mm × 6.5 mm and it was resolved by a CCD camera of 640 by 480 pixels. Four 2D phase maps of the specimen were obtained at four different wavelengths, and the exact fraction algorithm for the multi-wavelength interferometry algorithm was applied to derive the absolute height at each pixel. Figure 5 shows the measured 3D surface profile. The nominal step height of the standard flat bump was measured to be 69.642 μm with nanometer repeatability.

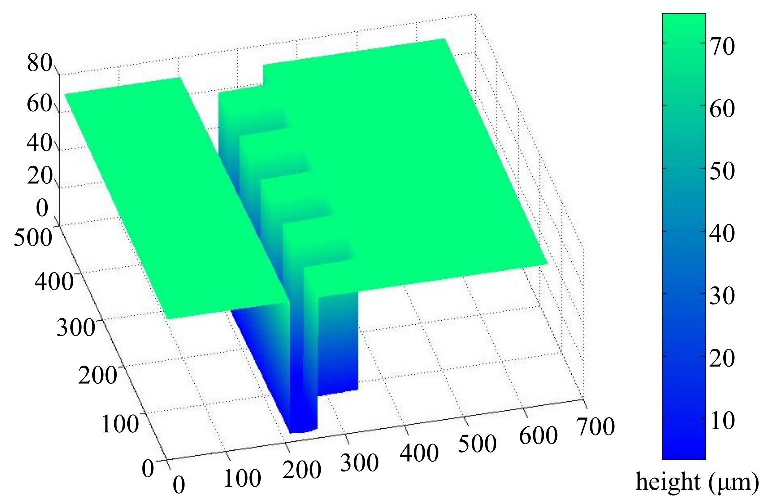

Figure 5. Measurement of high step-structures using frequency-comb-referenced multiple wavelengths. Reconstructed 3D surface profile of the standard step-specimen.

4. CONCLUSION

We demonstrated that femtosecond laser pulses can be used as a light source for fast and precise 3-D profilometry of microelectronic step-structures. Low-coherence scanning interferometry was realized by varying the repetition rate of femtosecond pulses through the unbalanced optical delay provided between the measurement and reference arms. All these measurement capabilities offered here are well-suited for fast 3-D profiling of large step-structures widely used in microelectronic products. In addition, frequency-comb-referenced multi-wavelength interferometry was demonstrated for the purpose of absolute surface profile metrology. The frequency comb was precisely stabilized to the Rb clock of frequency standard and four DFBs lasers were phase-locked to pre-selected modes of the frequency comb. The absolute surface profile of a 70 μm-step standard specimen was measured by incoperating with phase-shifting, A-bucket algorithm, and exact fraction method. These proposed interferometry systems using femtosecond lasers are expected to be applied to high-speed inspection of micro-electronic products with large-stepped structures such as semiconductors, flat panel displays and photovoltaic devices.

5. ACKNOWLEDGEMENTS

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