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Replication and dimensional quality control of industrial nanoscale surfaces using calibrated AFM measurements and SEM image processing

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ABSTRACT

Ultra-high precision manufacture of nanoscale structured polymer surfaces poses the highest challenges in terms of tooling and replication. This paper introduces new procedures for quality control of nickel stampers and polymer moulded discs for CD, DVD and HD-DVD manufacture: quantitative application of AFM to calibrate height, depth and pitch of sub-micrometer features and SEM image processing to detect replication accuracy in terms of number of replicated features. Surface replication is analyzed using a metrological approach: nano-features on nickel stampers and injection–compression moulded polycarbonate substrates are measured, measurement uncertainty calculated, replication fidelity assessed quantitatively, and dimensional tolerances at the nanometre scale verified.

1. Introduction

In the field of media support for both data storage and entertainment, polymer-based substrates composed of thin polycarbonate discs having a sub-micro structured surface (so-called optical discs) are nowadays the established format for a variety of different uses.

Since the beginning of its introduction, first at research and development level and then at the market place in 1982, the compact disc (CD) format attained a successful market position, reaching its peak of 15 billion CDs produced worldwide in 2001 [1,2].

The need for higher data content in both the entertainment sector (to achieve the shift from digital audio to audio/video content) and the electronic/information technology sector (increased data storage) created the motivations to enhance the capacity of the CD support and to develop the digital versatile disc (DVD) format which was introduced in 1996. Different strategies were adopted to increase the capacity of the media support, particularly related to drives and drive precision, multi-layer technology, encoding/decoding electronics (more powerful encoding methods and a redesigned logical format of the disc), and optics design. The latter dealt with the use of shorter laser wavelength and larger numerical aperture, which reduced the CD spot diameter from 780 nm to 650 nm. This has enabled to miniaturize the surface structures and therefore to increase data density [3]. The result was that a single-layer DVD has a storage capacity 7 times higher than the one of a CD and a double-layer DVD up to 14 times, equivalent to 135 min of wide-screen high quality video including multiple audio and subtitle channels. DVD production worldwide has grown since the format introduction into the market in 1998 with a peak in 2006 of about 10 billion discs and a market worth $100 billion [2,4].

Lately, starting from 2004, new formats appeared on the market in order to satisfy a renovated demand for increased capacity; for example, the high definition DVD (HD-DVD), capable of storing 15–30 GB on a single- and double-layer disc respectively. The drive for such increased capacity has been mainly the spreading of the High Definition Television (HD-TV) service which promoted the diffusion of high definition flat screens larger than 30 in. (in order to take advantage of the new TV format) with a market size of 7.6 million and 10.5 million units in Japan and USA respectively in 2006. As a consequence, high definition flat displays larger than 30 in. have shown the limitations of the current DVD format in terms of image quality and therefore the need for a new optical disc support, creating a technology gap to be addressed [4]. For the same reasons, also the Blue-ray Disc (BD-ROM) format, with a storage capacity of 25 GB, has been introduced. Both HD-DVD and BD-ROM present features with characteristic dimensions in the order of about 100–400 nm. In this paper, the focus will be on HD-DVD, as well as on CD and DVD.

2. Optical discs manufacturing process chain

Despite the different capacities of the three formats (CD, DVD, HD-DVD), the optical disc layout and process chain are basically the same. In particular, there is a first phase devoted to the manufacture of a master made of metal (typically nickel) and a second phase dealing with the production of polymer optical discs (typically made of polycarbonate).

2.1. Master making

After a pre-mastering phase (where a source material such as an audio/video recording or a computer software is converted

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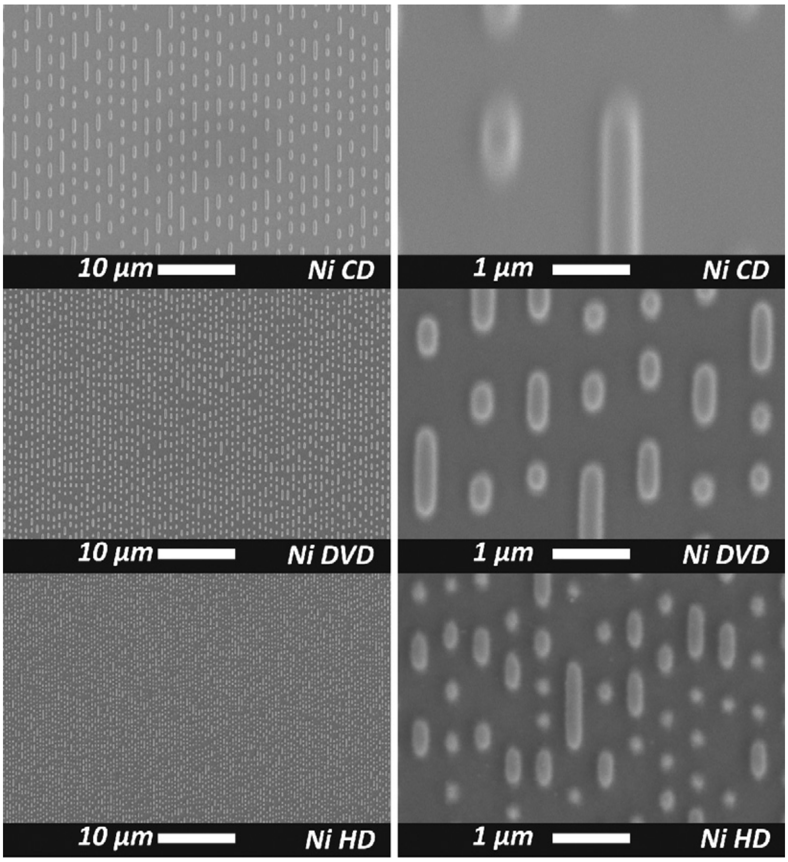

Fig. 1. SEM images of nickel stamper for optical discs moulding. The effect of increased data storage capacity by features miniaturization is shown on the three selected formats (CD top, DVD middle, HD-DVD bottom) both on a large surface (left) and on a detailed view (right).

into a digital format), the digital content is encoded by a mastering system and transferred to a glass master, inspected and then transferred to an electroformed nickel stamper under the form of sub-micrometer pillars (i.e. peaks) ordered on a spiral pattern at determined distances from each other (i.e. lands) (see Fig. 1). A stamper is defined as the particular mould employed to replicate optical discs such as CD, DVD or HD-DVD [5]. Typically, stampers have a diameter of 138 mm, a thickness of 300 μm with a 20–40 mm central hole. This first electroformed stamper (father) can be either used directly for polymer disc manufacturing, to shorten production times, or can be used for a galvanic process to produce other impressions (mothers). Such impressions are subsequently employed to manufacture nickel moulding matrices by electroforming (i.e. new stampers), obviously increasing the throughput of the production line [6]. In fact, the number of polymer discs made from the same stamper is mostly determined by the batch size rather than the stamper tool life, time-to-market being the crucial aspect on optical disc manufacturing industry [7].

2.2. *Polymer replication*

Nickel stampers are then fitted into an injection mould cavity formed between a mirror block and the stamper itself. By either a high-pressure/thin-wall injection moulding processes (CD) or an injection–compression moulding process (DVD, HD-DVD) the nickel stamper pattern is transferred into a polycarbonate disc (1.2 mm thick for CD, 0.6 mm thick for DVD and HD-DVD) in the form of shallow grooves of variable lengths (i.e. pits) positioned at certain distances (i.e. lands) along the spiral pattern (see Fig. 2). A high-grade polycarbonate resin is selected due to its excellent characteristics such as high transparency, dimensional stability, high flowability for accurate mould surface reproduction, minimum water absorption, good impact resistance, easy processing characteristics, and absence of impurities [8].

3. Nano-features dimensional quality control

The increased data storage density from CD, DVD to HD-DVD formats causes the decrease of the surface structure dimensions, challenging not only the tooling phase (i.e. stamper making process), but also the moulding process (i.e. replication fidelity within a very short moulding cycle time of 2–3 s). As a consequence, the product quality control (dimensional compliance to specifications) is a crucial step in order to validate process, processing conditions and production batch. In addition, due to the extremely short cycle time, online measurement of disc properties is desirable; therefore high measuring speed and data processing rate are of high importance. Research and applications [2,9–11] have dealt mostly with functional check of written tracks onto the disc surface at the production line end (e.g. quality control performed by playing a disc on a fast simulator employing a reading laser beam); digital image processing to detect opaque inclusions, holes, scratches; birefringence distribution measurements to ensure that internal stresses induced by the moulding process into the polymer do not prevent the disc to play correctly. Additionally, dimensional approaches to quality control of polymer optical disc structured surfaces were also investigated showing the capability of replicating features with height and track pitch respectively of 50 nm and 680 nm [11], 25–40–60 nm and 160–200 nm [12], 100 nm and 130 nm [13]. Atomic force microscopy (AFM) was in particular employed to measure the nanometre-sized features; however, the establishment of measurement traceability, the definition of replication fidelity parameters, the effect of downscaling from CD, DVD to HD-DVD both in the stamper and in the polymer replicas, as well as nano-structures dimensional compliance with specifications still need to be addressed. For these reasons, a metrological approach to control the replication quality of the stamper pattern into the polymer substrate as well as to the tolerance verification at nanometre dimensional scale was investigated applying AFM measurements.