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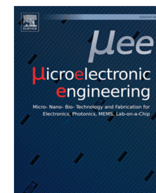

Research paper

A simple fabrication process for disposable interdigitated electrode arrays with nanogaps for lab-on-a-chip applications

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ABSTRACT

In this paper, we introduce for the first time a novel fabrication process for interdigitated electrode arrays (IDA) with nanogaps on polymer substrates. The IDA sensor for disposable lab-on-a-chip (LoC) applications employs an amperometric detection principle which allows a signal amplification by redox cycling. Our fabrication sequence is based on a lift-off free process and therefore, reduces the number of process steps and simplifies the fabrication and increases the yield. This innovative approach consists of an initial structure followed by two deposition processes. The initial structure, which is transferred into the polymer, is in the micrometer range and is formed by hot embossing. A silicon stamp is fabricated by mask aligner lithography and a subsequent dry etching step. An imprint template was prepared from the master and the structures are transferred into a 1 mm thick cycle-olefin polymer (COP) sheet. A subsequent sputter deposition process was carried out to form an undercut of the finger structures, which should guarantee a separation of the electrodes. A 90 nm thick gold layer was deposited by thermal evaporation to pattern the electrodes. The presented fabrication procedure represents an approach to fabricate disposable nanogap interdigitated electrode arrays allowing high signal amplifications in LoC applications. Furthermore, it demonstrates a low-cost method to fabricate IDAs with nanogaps for high volume mass production.

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1. Introduction

Since Bard et al. [1] demonstrated in 1986 a method to amplify the current signals for electrochemical detection, many different biosensor designs and fabrication techniques for interdigitated electrode arrays (IDAs) were introduced [2–11]. Biosensors employing IDAs are not only limited to amperometric detection but also are of interest for impedance based measurement methods [5,12–17]. Herein, most IDA sensors are build up on substrates like silicon or glass which push up prices and are not economical for disposable applications. Thus, the main disadvantage of the IDA-based biosensors is their relatively high fabrication costs. Furthermore, the great benefit of the electrochemical based biosensor is its capability to allow an amplification of the signal by redox cycling. This requires a short distance between the electrodes (in the sub micrometer range). The smaller the gap between the electrodes the higher is the achievable signal gain [18,19]. In such a case, the fabrication process requires a technology which supports this high resolution capability. In semiconductor industry, such technologies are available and structures in the sub 100 nm range are economical producible. Specific requirements on substrate and photoresist are essential to print such high resolution patterns: thin photoresist, defect free photoresist layer, substrate smoothness, etc. This results in higher costs and making the technology less attractive for single use and disposable applications. For a disposable LoC application, the substrate and the complexity of the fabrication process for the chip are determining the price. Therefore, polymer based materials fabricated with injection molding and hot embossing are preferred as they offer a cheap and simple production process. An integration of electronics into the disposable chip based on Si would raise the cost per chip dramatically. Consequently, the electronics should be realized by an external (handheld) device and should be combined with the disposable LoC cartridge. In this context different approaches were implemented or suggested to fabricate such biosensors on disposable substrates [20–23]. However, most processes include ether a pure resolution capability or high complexity. Zou et al. [22] demonstrated an interdigitated electrode array on a cycle-olefin copolymer (COC) wafer with e-beam lithography combined with conventional photolithography, achieving a 500 nm gap between the finger structures of IDAs. It shows the possibility to fabricate sub micro IDAs on a polymer substrate. Certainly, this process is quite complex. A simple fabrication approach would be to break down the process chain to a minimum and eliminating the lift-off process to

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improve the yield. Our fabrication process is lift-off free and consists of only three main processes: an initial structure which is fabricated by hot embossing, a deposition process to adjust the gap between the electrodes and a second deposition process defining the metal electrodes. This fabrication method overcomes the critical step of a lift-off process and allows the adjustment of the electrode gap with the first deposition process. Thus, a metal redeposition and a short-circuiting of the interdigitated electrodes are eliminated by the lift-off free approach.

2. Material and methods

In this paper, we present a simple IDA fabrication process for gap distances in the nanometer range on polymer substrates. The fabrication process as well as the electrochemical characterization of the COP chips were compared to silicon based chips. Both fabrication processes are lift-off free. The initial structure for the polymer based chip is fabricated by hot embossing, whereas the silicon based chip is produced by dry etching.

2.1. Chip design and process chain

The polymer nanogap IDA chip design with its main elements is illustrated in Fig. 1. The overall dimension of a single chip is 20 mm × 3.7 mm. Each chip is comprised of an IDA pattern with 300 finger pairs (two working electrodes WE1 and WE2), a reference electrode (RE) and a counter electrode (CE). The non-passivated areas are marked in blue.

The lift-off free fabrication process is illustrated in Fig. 2. The master stamp was fabricated in silicon and a soft process stamp was taken. This stamp was used for the pattern transfer into COP. The COP substrate with the initial structure was sputter coated with SiO_2 to form the undercut. The subsequent evaporation step for metal deposition defines the electrodes. Finally, the wafer was passivated with an isolation layer.

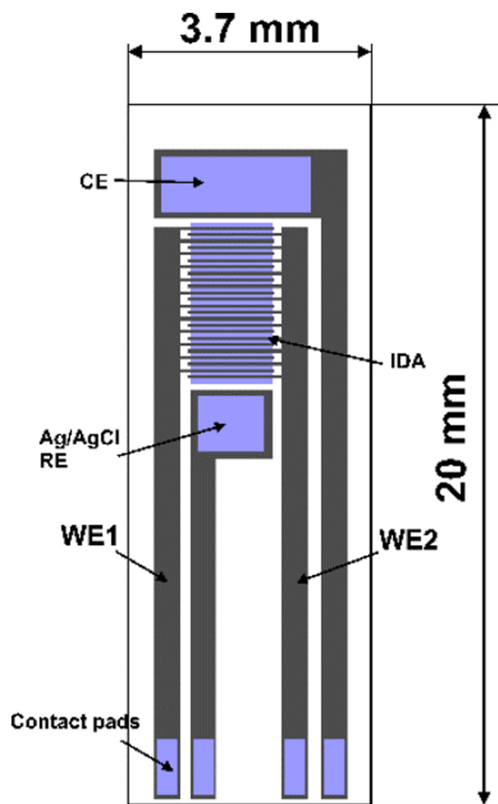

Fig. 1. Sketch of the polymer nanogap IDA chip design. The chip consists of two working (WE1, WE2), Ag/AgCl reference (RE) and counter electrodes (CE). The overall chip dimension is about 20 × 3.7 mm. (For interpretation of the references to color in this figure, the reader is referred to the web version of this article.)

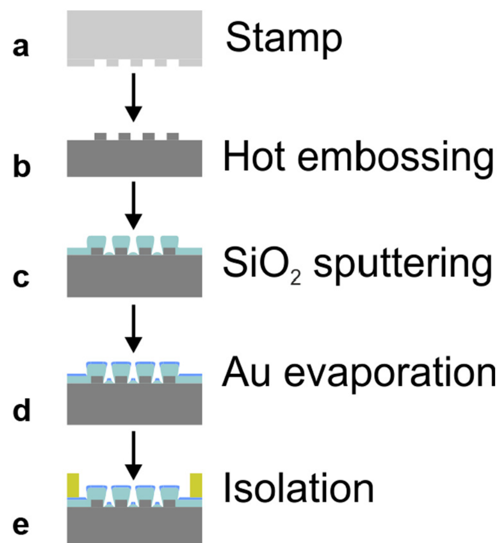

Fig. 2. Fabrication sequence of the disposable IDA-based sensor. (a) Silicon stamp; (b) hot embossing into COP; (c) sputter deposition of SiO_2; (d) deposition of Au; (e) definition of the measurement area by the isolation layer.

2.2. Detailed COP chip fabrication

The master stamp was fabricated on a standard silicon wafer. At the first step, the silicon substrate was spin coated with an adhesion promoter Ti Prime and subsequently with photoresist AZ 701 MiR to achieve a final film thickness of 760 nm. A softbake was performed on a hotplate at 90 °C for 1 min in contact mode. The vacuum contact mode was utilized to achieve the 1 μm line and space pattern for maximum accuracy during UV exposure. The chip design was fabricated on a quartz mask with features down to 1 μm. The optimum exposure dose was selected as 160 mJ cm^{-2} with i-line filter. The post exposure bake was performed on a hotplate at 110 °C for 50 s in contact mode. The developer AZ 726 MIF was used to dissolve the exposed areas for 45 s followed by a deionized water rinse (DI rinse). The photoresist pattern exhibits a smallest feature size of 1 μm, separated by a gap of 1 μm. The structures were etched 1 μm deep into silicon by a dry etching process with gas chopping technique (SF_6, C_4F_8) for 52 s. The photoresist was then removed using oxygen plasma.

Subsequently, the initial structures were replicated by hot embossing. The silicon master was replicated into a polymer working stamp [24]. A vacuum of 1 mbar between stamp and substrate was applied. At the next step the temperature is ramped above the glass transition point (Tg) of the substrate material and force is applied. A temperature of 173 °C and a force of 9 kN between stamp and substrate were applied for the imprints in this work. It takes about 3 min to fully transfer the structures into the COP substrate. Afterwards, the substrate is cooled down below Tg to solidify again and the stamp is detached from the imprinted substrate.

The undercut was formed by a reactive sputter deposition process with oxygen as the reactive gas and a Si target. SiO_2 was deposited in two different thicknesses, 500 nm and 700 nm. Next, a 10 nm thick titanium layer followed by 90 nm gold were evaporated to define the electrodes. In order to define the measuring area as well as the contact pads, a 2 μm layer of UV-curable hybrid polymer OrmoComp was spin coated. The polymer substrate was placed on a hotplate for 10 min at 80 °C to level the spin coated layer of OrmoComp. A dose of 1000 mJ cm^{-2} was necessary to obtain a sufficient polymer curing. An additional post exposure bake was performed on a hotplate at 80 °C for 20 min. The

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