Nanoscale GaAs metal–semiconductor–metal photodetectors fabricated using nanoimprint lithography

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GaAs metal–semiconductor–metal photodetectors (MSM PDs) with a variety of nanoscale finger spacings and widths were fabricated using nanoimprint lithography (NIL). Compared with MSM-PDs fabricated using electron-beam lithography and photolithography, the MSM-PDs fabricated using NIL do not show observable degradation in the device characteristics if the imprinting pressures are kept at 600 psi or below, although they do degrade at higher pressures.
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Nanoscale metal–semiconductor–metal photodetectors (MSM PDs)[1] and high-speed metal–semiconductor field-effect transistors (MESFETs) are key elements in optical and wireless communication systems. However, they are presently fabricated using electron-beam lithography (EBL), which has high cost due to low throughput, thus limiting the applications of nanoscale GaAs devices.

Nanoimprint lithography (NIL)[2] is a low cost, high throughput, sub-10 nm lithography. It has the potential to become a tool for the mass production of nanoscale GaAs devices. Previously, nanoscale silicon field-effect transistors have been fabricated using NIL.[3] However, compared with silicon, GaAs is very brittle and more susceptible to mechanical damage. Furthermore, GaAs cannot be heated to high temperatures to thermally anneal out the damage, as in the case of Si devices. Therefore, it is important to study the effects of NIL on GaAs device characteristics, such as surface damage of GaAs during imprinting and dry etching in pattern transfer. The Schottky contacts in MSM PDs are ideal structures to study these damages, because the current–voltage ($I-V$) characteristics of the contacts are very sensitive to the surface states and defects.

In this letter, we report the fabrication and characterization of nanoscale and micrometer-scale GaAs MSM PDs using nanoimprint lithography, compare them with MSM PDs fabricated using *e*-beam lithography and photolithography, and discuss the effects of different imprinting conditions on the detectors' characteristics.

In the NIL process, a MSM mold with interdigited fingers was first created on a silicon substrate. Next, a layer of polymethylmethancrylate (PMMA) was spun on a semi-insulating (SI) GaAs substrate. Before imprinting, both the mold and the PMMA-coated substrate were heated up to 175 °C, well above the glass transition temperature of the PMMA (105 °C), where the polymer becomes a viscous fluid. The mold was then pressed into the PMMA to create a thickness contrast pattern in the polymer. The NIL pressures used for PMMA resist are typically around 600 psi, although patterns can be successfully imprinted with a pressure as low as 300 psi. The effects of different pressures will be discussed later in this letter.

After the temperature was cooled down, the mold was separated from the substrate. The thin residual resist in the recessed region was removed by a 60 s anisotropic oxygen reactive ion etching (RIE), carried out in a PlasmaTherm-2486 system, with the rf power, pressure and O_2 flow rate kept fixed at 150 W, 3 mTorr, and 6 sccm, respectively.

The molds used for the experiment were patterned using EBL and photolithography. Typical mold intrusion features were from 190 to 330 nm deep, which was optimized according to the feature size of the MSM pattern.

To compare the effects of NIL with other lithography techniques, we also patterned reference MSM samples by photolithography and *e*-beam lithography, with a custom-built high resolution electron-beam lithography system converted from a JEOL-840 scanning electron microscope operated at 35 keV.[4]

To ensure a good comparison, the samples fabricated by NIL and other lithography methods were processed together after the pattern definition steps mentioned above. The common process steps included a 30 s dip in diluted HCl solution

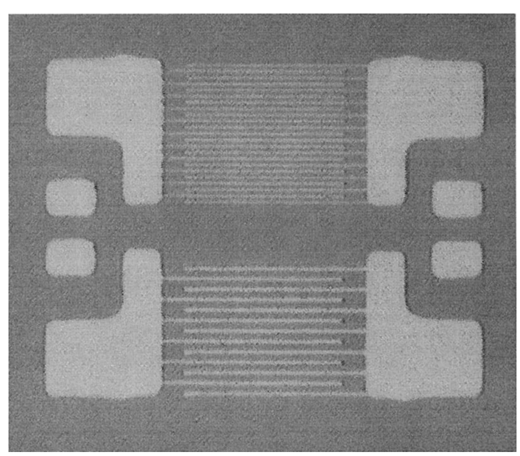

FIG. 1. GaAs MSM photodetectors with finger spacing of 300 and 600 nm, respectively, fabricated using nanoimprint lithography.

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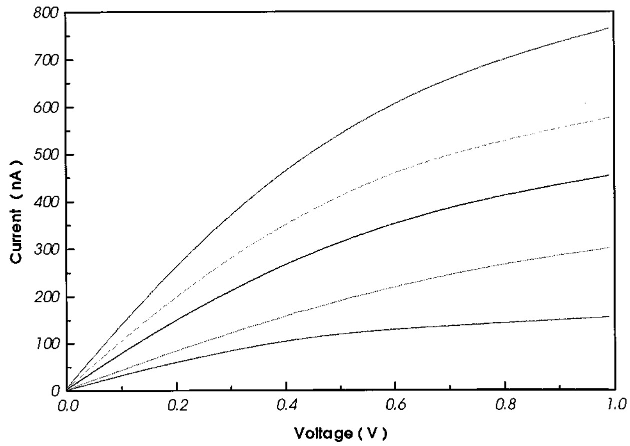

FIG. 2. The current–voltage characteristics with different incident light intensities of a GaAs MSM photodetector fabricated by NIL. The finger spacing is 500 nm.

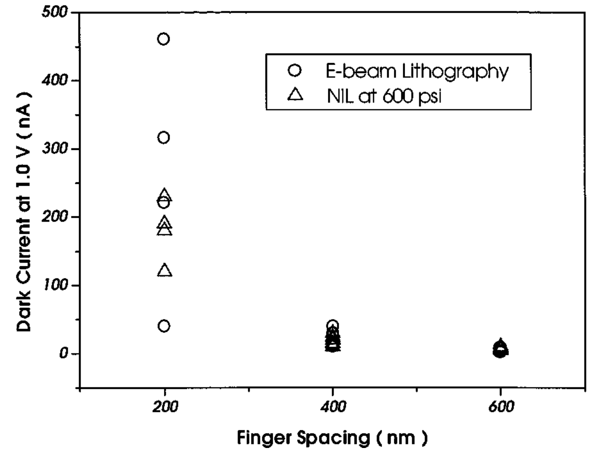

FIG. 4. The dark currents at 1.0 V of MSM PDs fabricated using EBL and nanoimprint lithography (imprinted at 600 psi). The finger spacing is 200, 400, and 600 nm. The dark currents for the samples with 200 nm finger spacing are widely distributed.

followed by a 2 min rinse in de-ionized (DI) water for the removal of surface contaminants. After that, Cr/Au was evaporated on both to form the Schottky contacts.

The MSM PDs fabricated by EBL and NIL had finger spacings and widths of 200, 300, 400, 500, and 600 nm and a detection area of $14\,\mu m \times 14\,\mu m$ (Fig. 1). The MSM PDs fabricated using photolithography and NIL had finger spacings and widths of 0.9, 1.7, and 2.0 μm with a detection area of $26\,\mu m \times 23\,\mu m$. The electrical properties $(I-V)$ were characterized using an HP 4145B semiconductor analyzer.

Figure 2 shows the typical dc characteristics of a 500 nm finger spacing GaAs MSM PD made by NIL at different illuminations. The $I-V$ curves, which are similar to those fabricated by EBL, do not show perfect saturation because of surface recombination centers.[1]

The MSM PDs' dark currents were measured at 1.0 V bias. Figure 3 compares the dark currents of the MSM PDs fabricated by photolithography and NIL at a pressure of 600 psi. There is no observable difference in the dark currents.

Figure 4 compares the MSM PDs fabricated by EBL and NIL at a pressure of 600 psi. We found that when the metal finger spacing was larger than 300 nm, the MSM PDs fabricated using NIL were identical to those fabricated using EBL. For those devices with finger spacing less than 300 nm, there were large variations in the average value and width of distribution of the dark currents for both EBL and NIL samples. The variations, which were associated with the increase of the electrical fields between the metal fingers, prevented a good comparison in that device size range.

The samples compared in each figure are from the same processing batch, because variation was also observed for different processing runs. In spite of that variation, for the samples from the same batch, the difference between the reference samples (by EBL or photolithography) and those fabricated by NIL (at 300 and 600 psi) was not observed.

To study the effects of imprinting pressures on the GaAs MSM PDs' characteristics, we fabricated MSM PDs on GaAs which were imprinted under different pressures: (1) 600 psi, which is the typical pressure for imprinting in PMMA; (2) 300 psi, a pressure lower than the typical value but the pattern can still be successfully transferred; (3) 900 psi, which is higher than the usual NIL pressure.

The results are shown in Figs. 5 and 6. No apparent differences in $I-V$ were observed between those samples imprinted at 600 and 300 psi. However, a significant device

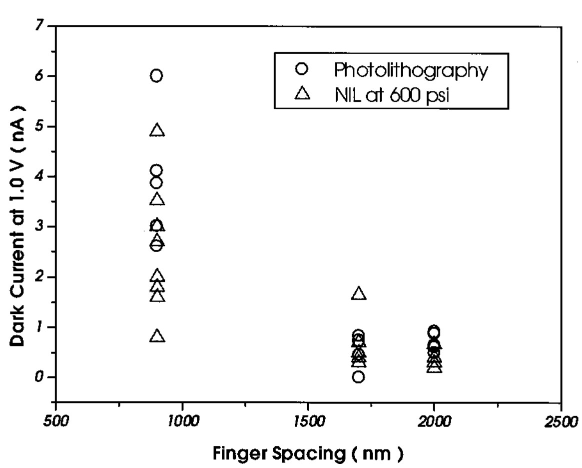

FIG. 3. The dark currents at 1.0 V of MSM PDs fabricated using photolithography and nanoimprint lithography (imprinted at 600 psi). The finger spacing is 0.9, 1.7, and 2.0 μm. Within the measurement error, the photodetectors fabricated by NIL and photolithography are identical.

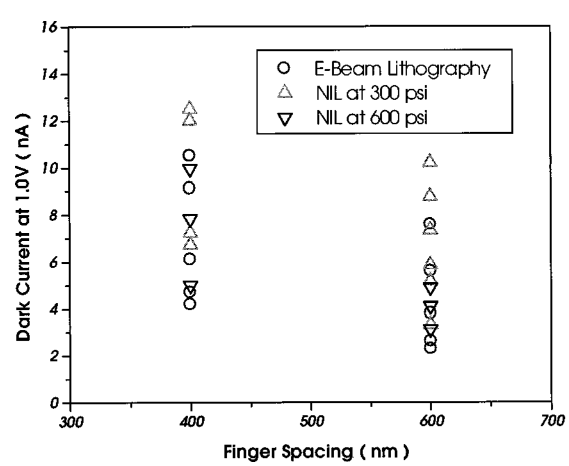

FIG. 5. The dark currents at 1.0 V of MSM PDs fabricated using EBL and nanoimprint lithography (imprinted at 300 and 600 psi). The finger spacing is 500 and 600 nm. The difference between them is not observable.

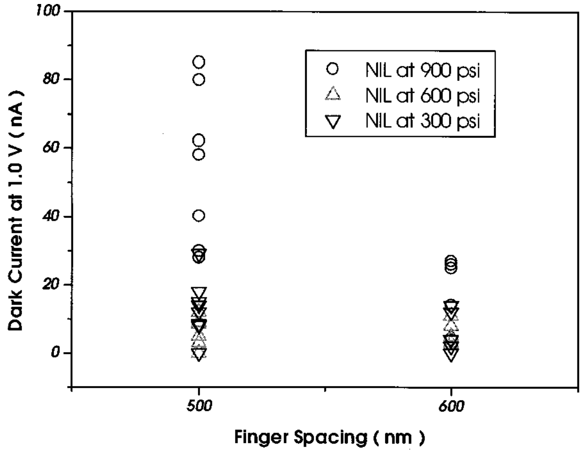

FIG. 6. The dark currents at 1.0 V of MSM PDs fabricated by imprinting at different pressures (300, 600, and 900 psi). The finger spacing is 400 and 600 nm. Degradation of the 900 psi samples leads to an increase in the average dark current and a wider range of variation.

performance degradation was observed for the MSM PD samples imprinted at 900 psi, where the average dark current was increased and the range of variation in dark currents was widened. This indicates that at 900 psi, there is significant pressure-induced surface damage, which degrades the Schottky diode contact between the GaAs substrate and the evaporated metal layers. Although surface damages to GaAs during different fabrication processes have been extensively studied.[5,6] Our experiment is the first study of the effects of NIL pressure on the GaAs–metal Schottky barriers. Furthermore, our experiments show that NIL has a higher resolution for patterning nanoscale features on GaAs than direct *e*-beam patterning because NIL does not suffer the proximity effect which limits the EBL resolution. Our experiment indicates that when the imprinting pressure is kept at 600 psi or below, NIL will not create noticeable degradation in the $I-V$ of GaAs MSM PDs.

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