In this paper, we present a new hot embossing process that enables high-resolution patterning of micro-structures on both flat and nonplanar substrates. In this process, a flexible elastomer stamp, i.e. PDMS, was used as the mold that performs hot embossing procedures on substrates of arbitrary curvatures. The new process was optimized through the development of an automated vacuum thermal imprinting system that allows precise control of all process parameters, e.g. pressure, temperature, and time. The new hot embossing process can be used to produce high quality microstructures of various geometries. Hexagonal micro-lens arrays were fabricated via the process to demonstrate its versatility and unique capability.

HARD MOLD VS. SOFT MOLD
Hot embossing was first proposed by Chou in 1995 for patterning high resolution structures on thermoplastic materials [1]. The process utilizes a hard mold containing nanoscale features. When in operation, the mold and the substrate are heated to the glass transition temperature and brought into contact to pattern polymers, e.g. PMMA, PS, PC, and PE, generating nanoscale features of 25 nm with good throughput [1]. However, using a hard mold may have the following drawbacks: (1) small features in the mold can be easily polluted and difficult to clean due to polymer adhesion, and (2) pressure distribution during molding is non-uniform which limits the accuracy and area of replication and may even damage the mold. (Substrates are never flat at nanoscale.)

Compared with the conventional hot embossing process, a soft elastomer mold has the following advantages: (1) elastomeric molds are low cost and can be easily replicated from a master; (2) the flexible mold enables conformal contact and uniform pressure distribution during molding; (3) elastomer molds, e.g. polydimethylsiloxane (PDMS), are chemically inert and anti-adhesive to polymers and can be easily demolded without cracking when compared with the hard mold.

SOFT MOLD PREPARATION
PDMS was chosen as the material for the soft mold in our new process because PDMS is thermally stable up to 200°C with low surface energy. Figure 1 illustrates the fabrication process of a PDMS mold. First, a master with hexagonal micro-lens array patterns was fabricated by the photolithography process and subsequently the thermal reflow process. Then, the PDMS mixtures (10:1) were spin-cast to the master. After curing, the PDMS forms the soft mold of desired thickness.

VACUUM THERMAL IMPRINTER DESIGN
To scale up and execute the new hot embossing process with precision, a vacuum thermal imprinting system was conceptualized and developed based on the vacuum imprinting system reported in [2]. Figure 2 shows the schematics of the imprinting system, where the PDMS mold is installed in the middle of the chamber, separating the room into two independent chambers (A and B). The substrate is placed in the bottom chamber. Independent air valves and pressure sensors are used to control the pressure difference between the top (A) and bottom (B) chambers. An infrared lamp is installed in chamber A to provide heat for hot embossing. In addition, a load cell is integrated with the substrate holder in chamber B to monitor the printing force in real time. A thermocouple is installed in chamber B to measure and control the temperature.

Figure 3 illustrates the thermal imprinting procedure. Step 1: Both chambers are vacuumed and the IR lamp heats up the
substrate to the molding temperature; step 2: chamber A is pressurized to deform the flexible mold to perform a hot embossing process; step 3: the substrate is cooled down to the demolding temperature with controlled imprinting force; step 4: demolding is performed by pressurizing chamber B.

EXPERIMENTAL RESULTS

We have fabricated and characterized the hexagonal micro-lens array on a convex PMMA substrate to demonstrate the new hot embossing process as well as performance of the vacuum imprinting system. Figure 4 presents the experimental data for the thermal imprinting process as illustrated in Figure 3: At first both chambers were pumped down to 4psi as the temperature was raised and maintained at 200°C, higher than the PMMA glass-transition temperature, i.e., T_g=105°C. In the embossing stage, the pressure in chamber A was raised and lowered in a cyclic fashion to remove the trapped air in the micro-cavities [2]; in the cooling stage, the temperature was lowered to 70°C. Figure 5 shows the results of a patterned hexagonal micro-lens array (left) on a convex PMMA substrate and the surface profile of micro-lenses (right) with an average diameter of 180 µm, pitch of 28 µm and sag height of 19 µm.

CONCLUSION

We have developed a new hot embossing process using soft PDMS molds that enable batch fabrication of high aspect-ratio precision micro-structures on nonplanar substrates at low cost. A vacuum thermal imprinting machine was constructed to precisely control the operating parameters. Micro-lens arrays were patterned on a convex substrate for demonstration.

REFERENCES