INTRODUCTION

Advancements in the fields of optical communication, photonics and display technologies require the development of high volume, high precision production methods. As signal traffic continues to increase on fiber optic networks, there is a need to perform switching without converting the optical signal to an electric signal. These switches, often called Micro Optical Electro-Mechanical Systems (MOEMS), must be fast, durable, highly transmissive, and thermally stable. Video displays on laptop computers and personal organizers are increasing in quality and there is a constant demand for wider viewing angle and screens with increased brightness and clarity. Display applications also require components that are thin, precisely located over a large area, and highly transmissive. Both fields require high-volume, low-cost fabrication and assembly techniques.

Molded polymers fulfill many of the requirements for these parts, but still present challenges. For example current production methods for MOEMS rely on integrated circuit technologies such as lithography and flip-chip construction. These methods require many steps with precision alignments of successive masks to produce the desired features. The components are built up from silicon in the z dimension and then separated from the substrate and rotated to produce in-plane optical networks on the substrate [1]. Replicated polymer optics would serve well in this application if they could be thermally stable throughout the wide temperature operating range and provide long service life. One potential solution is to mold the polymer optics in a thin layer on a thermally stable substrate [2]. Such optics could be cast in a UV curable polymer [3] (low volume production, low capital investment) or injection molded (high volume production, high capital investment). The application of thin polymer optics on a thermally stable substrate would also benefit the field of display technology where laptop and personal organizer screens require microlenses and optical waveguides on the glass screen substrate to broaden the viewing angle or to sense the touch-input device.

The goal of this research involves the development of processes capable of accurately reproducing sub-micron optical features over small and large areas as well as rapidly co-molded these features on thermally stable substrates.

REPLICATION TECHNIQUES

UV Cure Molding

UV cured polymers have been extensively used for creating soft contact lenses and also for replicating thin optical surfaces on top of glass and plastic substrates [7, 8]. This process was studied to evaluate the capability to reproduce nanometer sized features on the mold and also the speed and repeatability of the process.

An aluminum mold was diamond turned with the mold cavity 350 µm deep. The monomer was cast into the aluminum mold and the mold placed in a vacuum chamber to remove entrained air.
bubbles. Upon removal from the vacuum chamber, a glass plate was placed over the cavity. UV illumination cross-linked the monomer and it adhered to the glass plate. While features were accurately replicated within a few nanometers, this process is quite slow. To reduce the cycle time of this operation, investigation into injection molding was initiated.

**Injection Molding**

To achieve the goal of precision replication of sub-micron features in thin moldings over a large substrate in injection molding, the research has been divided into four stages:

The first stage investigated the transfer of feature and form from the mold to the molded part. Previous research [4, 5, 6] reported the molding variables that affect feature transfer, but further study is warranted for optical components. Tests were conducted using a diamond-turned mold producing a 25 mm diameter plano-convex lens with center thickness of 3.5 mm. The plano mold half had features ranging between 0.5 and 16 µm width with depths less than 21 nm.

The second stage will investigate the injection molding of part geometries onto thermally stable substrates such as glass, and quartz using the convex half of the mold in conjunction with a plano substrate located in the fixed side of the mold base.

The third stage of the project will combine the molding of very thin parts onto thermally stable substrates.

The fourth stage will investigate the transfer of micron and sub-micron features within the very thin parts on thermally stable substrates, possibly incorporating precision slides to produce in-plane optics.

**Concave-Plano Lens** A Van Dorn, 75 ton hydraulic injection molding machine was used to fabricate test lenses. Two mold halves, one plano (fixed half) and the other concave (to make a convex lens) were diamond turned from aluminum and installed in the mold bases on the machine. VEREX 1301 polystyrene (Nova Chemicals) was injection molded with varying hold times, cooling times, and barrel temperature profiles to determine the optimum parameters for form and feature transmission. An injection pressure of 11.4 MPa was held constant for all trials. The hold time was varied between 2 and 20 seconds while maintaining a constant injection pressure, barrel temperature profile, and cooling time. Subsequently, the in-mold cooling time was varied between 4 and 20 seconds while maintaining a constant barrel temperature profile, holding time, and injection pressure.

The barrel temperature test varied the temperatures at the three control locations along the injection barrel. The machine controls the temperature using a PID controller that monitors the temperature at the front and rear of the barrel and at the injection nozzle. Electric heater bands at each location maintains the desired temperature. The temperatures were varied between 215°C and 265°C. The process temperature range published for the polystyrene is between 190°C and 274°C, but the entire range was not available using the other molding parameters as set due to the melt and flow characteristics of the polymer.

**RESULTS AND DISCUSSION**

**UV Cure Molding** Figure 1 illustrates the quality of the UV polymer replication. Figure 1(a) is a white-light interferometer trace of a diamond turned mold and Figure 1(b) is an inverted trace of the plastic replica. The surface has the characteristic features of diamond turning with a slightly-damaged tool resulting in a rms roughness of 20 nm. The feed rate for this surface is
about 20 µm per revolution. The replicated surface is inverted to make it easy to compare the mold and replica. The small features of the tool (some less than 10 nm) are copied with impressive fidelity using UV cure polymers.

Figure 1 (a). White Light interferometer trace of diamond turned aluminum mold surface

Figure 1(b). Inverted white-light interferometer trace of UV cured polymer replica

Figure 2 shows a top-down view of the center of a second diamond turned mold. In this case the feed rate 20 µm using a 3 mm tool radius. The theoretical height of the features is 15 nm.
Injection Molding  A large number of test parts were fabricated with varying packing time, barrel temperature and barrel temperature. The figure of merit selected was the peak-to-valley error on the flat side of the molded lens. Flat features are the most difficult to mold so this measurement was deemed a useful comparison. A significant reduction in form error (on the order of 75%) was observed as the time was increased from 1 to 10 seconds. The influence of cooling time was less apparent. While a slight downward trend was observed (increased cooling time reduced form error), more scatter in the data also existed for these tests. The results of the barrel temperature profile tests showed similar scatter. Additional tests are in progress to better define the trends.

REFERENCES