MEMS Digital Camera

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ABSTRACT

MEMS technology uses photolithography and etching of silicon wafers to enable mechanical structures with less than 1 um tolerance, important for the miniaturization of imaging systems. In this paper, we present the first silicon MEMS digital auto-focus camera for use in cell phones with a focus range of 10 cm to infinity. At the heart of the new silicon MEMS digital camera, a simple and low-cost electromagnetic actuator impels a silicon MEMS motion control stage on which a lens is mounted. The silicon stage ensures precise alignment of the lens with respect to the imager, and enables precision motion of the lens over a range of 300 um with < 5 um hysteresis and < 2 um repeatability. Settling time is < 15 ms for 200 um step, and < 5ms for 20 um step enabling AF within 0.36 sec at 30 fps. The precise motion allows COTS optics to maintain MTF > 0.8 at 20 cy/mm up to 80% field over the full range of motion. Accelerated lifetime testing has shown that the alignment and precision of motion is maintained after 8,000 g shocks, thermal cycling from -40 C to 85 C, and operation over 20 million cycles.

Key words: MEMS, micro, mechanical, camera, silicon, reliability, cell phone, camera-phone

1. INTRODUCTION

The reduction in size for digital cameras is not a new phenomenon. Consumers have consistently demonstrated a buying preference for smaller digital cameras, as long as the image quality was not significantly compromised. This trend has been dramatically accelerated by the integration of digital cameras into cell phones, but technology has not managed to keep up.

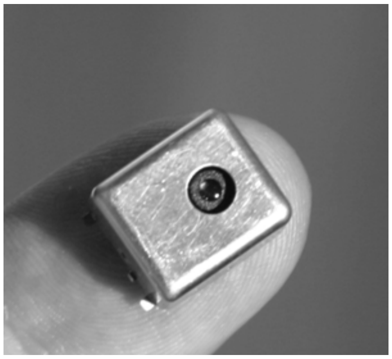

Figure 1. Photograph of a 2 MPixel MEMS digital camera for use in cell phone.

The reduction in size of a digital camera leads to several fundamental technology issues that are challenging the industry. As the size of an optical system is reduced, ray tracing indicates that the optical performance should not change so long as the optical system operates above the diffraction limit. In practice, however, the performance of an optical system is largely dependent on the alignment tolerances of the optical elements. As the optical system is reduced in size, these tolerances have to be reduced in proportion in order to maintain the same optical performance. Thus, the reduction in size of a camera, if maintaining a similar optical performance, is limited by the tolerance of the manufacturing technologies that are utilized. For example plastic injection molding and metal stamping have tolerances of about 25 microns, and these tolerances are already used to their limit in relatively large stand-alone digital cameras.

MEMS (micro-electro-mechanical-systems) technology uses photolithography and etching of silicon wafers to enable moving mechanical structures with less than 1 micron tolerance. This technology enables the required improvement in alignment tolerances needed for high performance miniature digital cameras in cell phones.

2. DESIGN

A photograph of a 2 Mpixel digital camera using MEMS technology is shown in Figure 1. The size of the camera is 11.5 mm by 11.5 mm by 8.5 mm, including the shield and the electronics board. Inside this camera, a MEMS stage is used to control the motion of an optical lens barrel with high precision. This allows the camera to adjust its focus position from 10 cm to infinity while maintaining a high quality and high resolution picture.

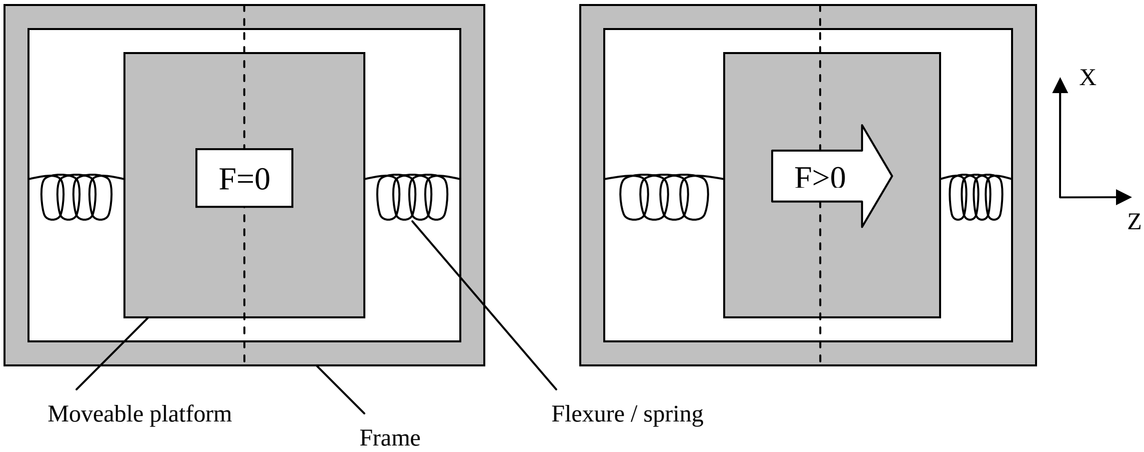

Figure 2. Conceptual diagram of the MEMS stage. A movable platform is attached to a frame through flexures or springs. When there is no external force on the platform (left), it is at a neutral resting position. When an external force is applied (right), the platform moves with respect to the frame to a new equilibrium position.

The central element of this camera, responsible for the precision motion control, is the MEMS stage. A conceptual diagram of the MEMS stage operation is shown in Figure 2. The stage has a movable platform that is connected to a frame through flexures or springs. The position of the platform with respect to the frame is dependant on the external force that is applied to this platform. In the absence of any external force (F=0 in Figure 2), the position of the moveable platform with respect to the frame is purely determined by the flexures, and corresponds to the position of lowest stress in these flexures. When a force is applied to the moveable platform (F>0 in Figure 2), it moves to a new position that balances the restoring force of these flexures with the external force. To change the position of the moveable platform, the external force is changed. In order to ensure that the motion is linear, it is usually not sufficient to ensure that the actuation force is linear, since there are a number of external forces present on the moveable platform (e.g. gravitational forces). As a result, the flexures must be designed to constraint the motion by ensuring that the spring stiffness is significantly softer (e.g. 1,000 times) in the Z-axis than in all other five degrees of freedom. An innovative flexure design (patents pending) is used that takes advantage of the high aspect ratio achievable in silicon micromachining to fabricate a stage with the desired stiffness ratios. A photograph of the MEMS stage and a close-up Scanning Electron Microscope (SEM) photograph of a portion of the flexure are shown in Figure 3. The width of the flexures is only about 10 microns, while the thickness is about 300 microns.

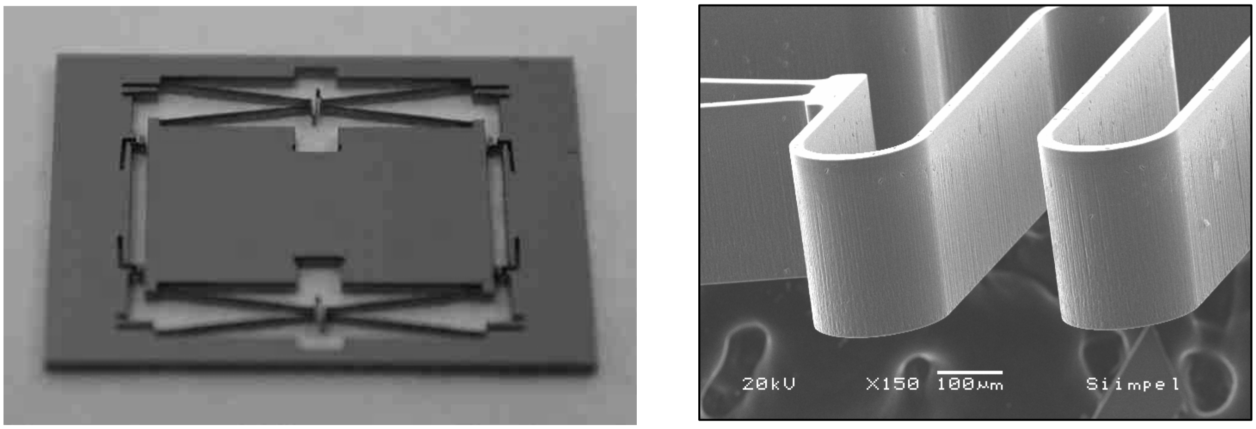

Figure 3. Photograph of a MEMS stage (left) and SEM of silicon flexure (right) used to move a lens for autofocus.

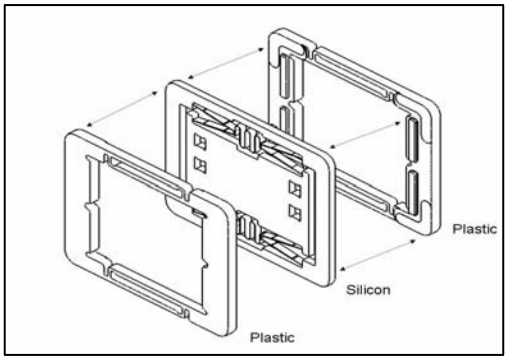

Figure 4. Exploded view of a packaged stage.

Figure 5. Photograph of 432 packaged MEMS Stages on a tray.

The MEMS stage is made out of single crystal silicon by using photolithography and Deep Reactive Ion Etching (DRIE). Approximately 500 of these devices are made in parallel on a silicon wafer using a simple single mask process. Because the stage is monolithic, the position of the moveable platform is determined with photolithographic precision (< 0.1 microns) with respect to the frame, solving one of the key issues related to the miniaturization of autofocus systems for digital cameras, which is control of the position in six degrees of freedom of a moving lens barrel with respect to an imager.

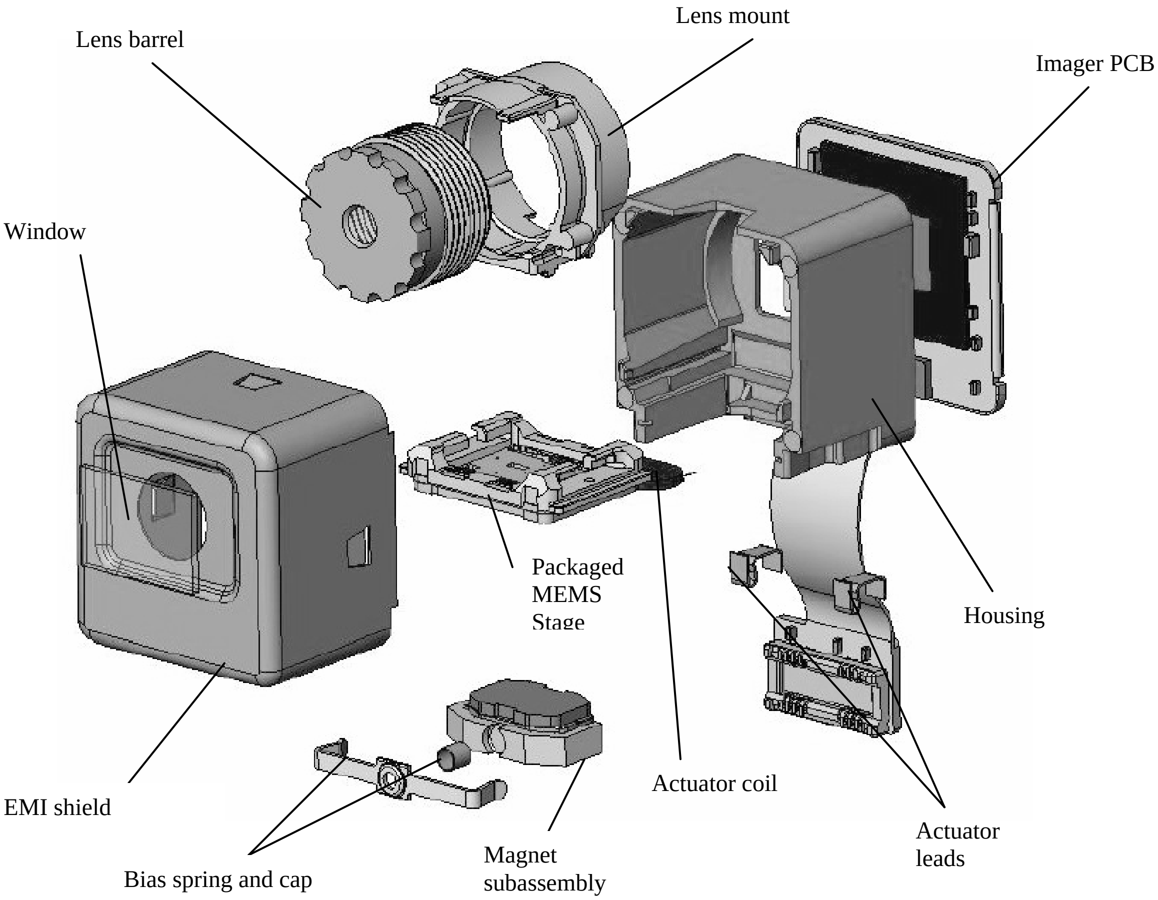

Figure 6. Exploded view of a MEMS digital camera shows all components used in the assembly.

The MEMS stage is packaged using two plastic caps to ensure that the flexures are not damaged during shipping or shock. The assembly process is illustrated in Figure 4. Two plastic parts are attached on either side of the silicon stage, enclosing the frame but leaving the moveable platform accessible. A photograph of 432 packaged MEMS stages on a tray is shown in Figure 5.

An exploded view of the MEMS digital camera is shown in Figure 6. The packaged MEMS stage is the central component and serves as an optical bench to which all other components are mechanically aligned. A lens mount is attached on the top surface of the moveable platform, while a magnet subassembly is attached to the bottom surface of the moveable platform. The total payload mass, including the lens barrel that is screwed into the lens mount, is approximately half a gram. The magnet subassembly is the moveable part of the electro-magnetic actuator. The frame of the stage is attached to the inside of the housing, on which the coil (stationary part of the actuator) is also mounted. The housing aligns the coil inside the magnet subassembly, where there is a large permanent magnetic field. The coil is not in physical contact with the magnet subassembly, but can transfer a force to it through the interaction between the magnetic field generated by the electric current in the coil and the magnetic field in the magnet subassembly. A bias spring is compressed between the magnet subassembly and a spring cap that is mounted to the housing. This bias spring places a force on the moveable platform to ensure that the position of the lens is fixed at infinity focus when there is no current running through the coil. The housing not only serves to align the coil to the stage, but also serves to align the imager to the stage. The imager is mounted on a plain circuit board (PCB), and the PCB is attached to the housing. Therefore, the alignment of the lens barrel to the imager depends on the alignment of the lens barrel to the lens mount, the alignment of the lens mount to the stage, the alignment of the stage to the housing, the alignment of the housing to the PCB and the alignment of the imager to the PCB. The alignment of the lens mount to the stage is simplified by high precision alignment holes in the silicon stage and corresponding mating feet on the lens mount. It is also worth noting that although there are still significant stack up errors in alignment that depend on injection molded parts, the silicon stage greatly simplifies this alignment by ensuring that the moveable platform of the stage is perfectly aligned in all degrees of freedom to the frame.

3. TESTING

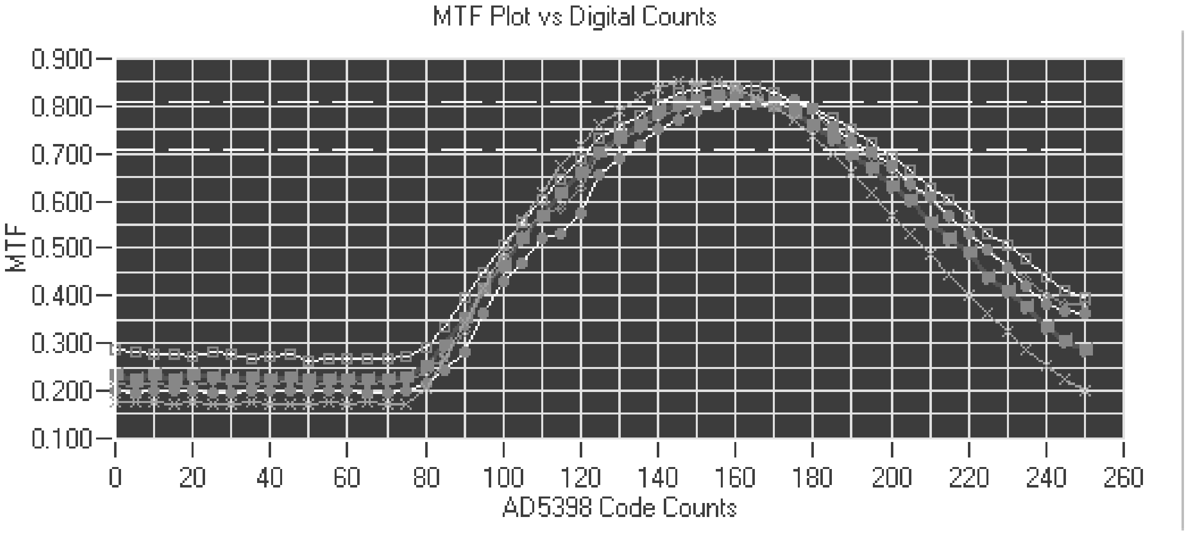

Figure 7. Optical performance measured by Modulation Transfer Function (MTF) at 20 cy/mm as a function of the control signal to the autofocus actuator. The five curves represent MTF measured at the center and all four corners (80%) of the image.

A 2MP version of this MEMS digital camera has been assembled and tested. The performance of the camera is evaluated using a custom software developed at Siimpel, which evaluates the Modulation Transfer Function (MTF) as a function of lens position. The actuator coil is driven using Analog Devices chip AD5398, which is a current sinking Digital to Analog Converter (DAC). The chip is capable of sinking up to 120 mA, but only up to 60 mA of current is used for this actuator. The software controls the AD5398 through the I2C interface and sets the DAC to a code between 0 and 256 (8 bits), corresponding to a current between 0 and 60 mA. For every setting of the AD5398, the camera is commanded to take a picture of a slanted edge target, and the software calculates the MTF at the center of the image and at each of the four corners, at 80% of full image diagonal. The MTF calculated by this custom software has been compared with commercially available software such as Imatest as well as the software used by our customers and there is a good correlation. A plot of the MTF as a function of AD5398 code is shown in Figure 7. In this case the target was placed 30 cm away from the camera, so the peak in MTF is at a code count of about 160. The horizontal lines at 80 % MTF and 70% MTF (20 cy/mm) is what is generally considered acceptable performance for a 2MP camera for the center and corners (80% of image diagonal) respectively. As expected, the MTF drops below the acceptable level when the lens is not properly positioned, illustrating the need for autofocus for 2MP resolution imagers. When the lens is placed at infinity focus, as it is for a fixed focus camera, this test shows that the MTF drops below 30%, which practically means that the camera would not be able to resolve features corresponding to 20 cy/mm on a 1/3” optical format imager.

Figure 8. Photographs taken with a 2 MP MEMS digital camera of a scene with objects at various distances from the camera, focused on the furthest objects (left) and the nearest (right).

Photographs taken with the 2MP digital MEMS camera of a more natural scene, shown in Figure 8, clearly illustrate the effect of the autofocus on the resolution of the objects at various distances from the camera. For the picture on the left, the camera is focused near infinity, since the background is about 1.5 meters away, which is very close to the hyperfocal distance for the camera. For the picture on the right, the camera is focused to 10 cm, which is the distance to the object on the bottom-right corner. Even though these images are reproduced here in a very small format, without color, and with low resolution, the difference between the two pictures should be easily discernable. Objects between 10 cm and infinity appear out of focus in both images and require an intermediate lens position to be in focus.

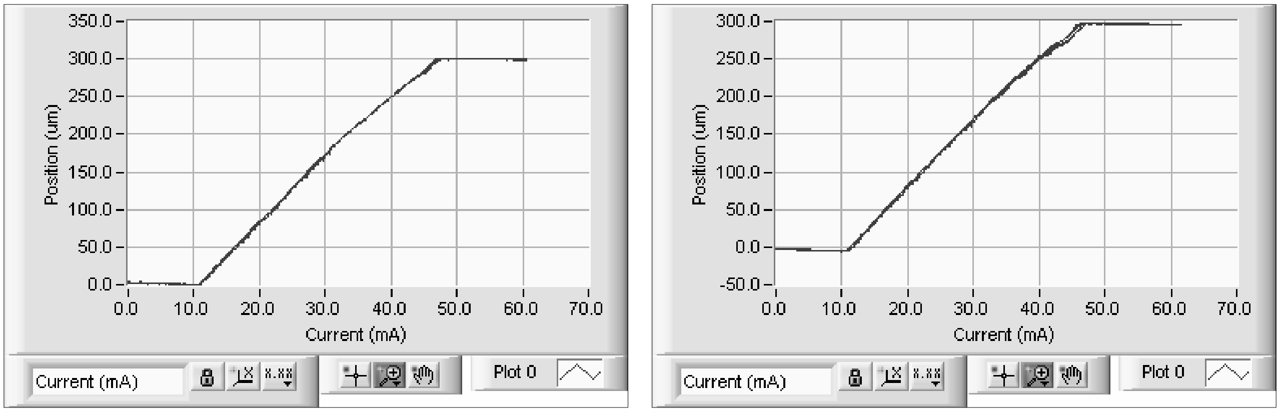

Figure 9. Plots of lens position vs. current before (left) and after 36 drops inside a cell phone from 4 feet onto concrete (right).

In addition to measuring camera performance, we have developed a system to measure the position of the lens directly using laser metrology. Using this system, we are able to measure the position of the lens as a function of the current flowing through the coil, as shown in Figure 9. The threshold current is defined as the current that is needed before the actuator has enough force to overcome the force of the bias spring, which is holding the lens against the infinity focus position. In this figure, it can be seen that this is approximately 10 mA. Once the threshold current is exceeded, the lens moves linearly in response to increasing current. Once the current reaches about 45 mA, the stage has traveled 300 micrometers and the lens reaches its end of travel. Further increase in current beyond this point does not change the position of the lens.

The plots shown in Figure 8 actually show data from ten consecutive cycles, where, in each cycle, the current is ramped from 0 mA up to 60 mA and then from 60 mA down to 0 mA. In this way, repeatability and hysteresis are measured. Hysteresis is calculated as the difference between the position of the lens at a certain current when the current is being ramped up versus when the current is being ramped down. In this case, the hysteresis is less than 5 micrometers. Repeatability is a measure of the difference in the position of the lens at a certain current from one cycle to the next. Repeatability is less than 2 micrometers. Given that the depth of focus of lenses used for a 1/3” optical format imagers is typically around 20 micrometers, these values of hysteresis and repeatability ensure a high degree of repeatability in the autofocus algorithm, which translates to a higher success rate in reaching the desired focus position.

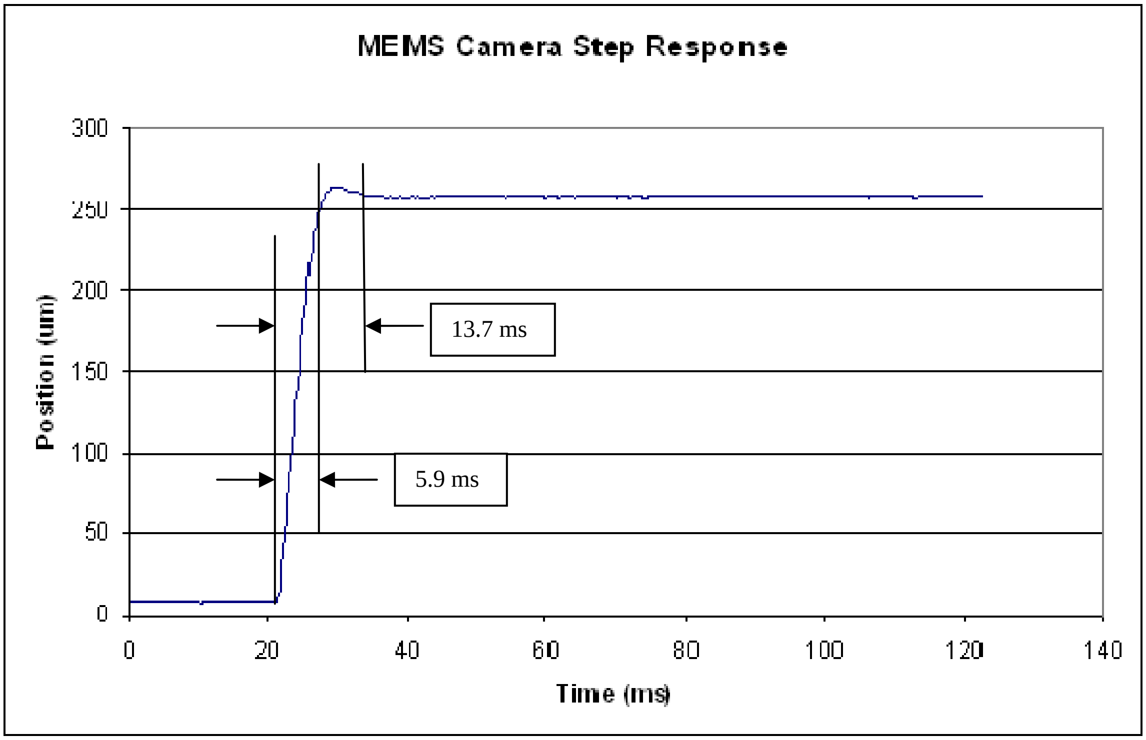

Figure 10. Step response of the MEMS digital camera.

Another interesting test we carry out on these cameras is to determine the speed of the actuator when commanded to switch from one position to another. This is important for autofocus (AF) since the lens position needs to be quickly changed so that pictures can be taken at full frame rate and without skipping any frames. Figure 10 shows the step response for a 250 micrometer step. The position is measured using the laser based system previously described. In this case, the lens reaches within one focus zone (20 micrometers) of the final position in 5.9 ms. The time to completely settle in its new position is 13.7 ms. In all cases, the smaller steps can be made within 5 milliseconds, while larger steps can be made within 15 ms. At 30 frames per second (fps), pictures are taken every 33 ms, but only approximately 15 ms is available to move the lens from one position to the next. The ability to switch position withing 15 ms means that no frames are skipped during AF. As a result, these cameras achieve fast AF speeds of less than 0.36 seconds at 30 frames per second.

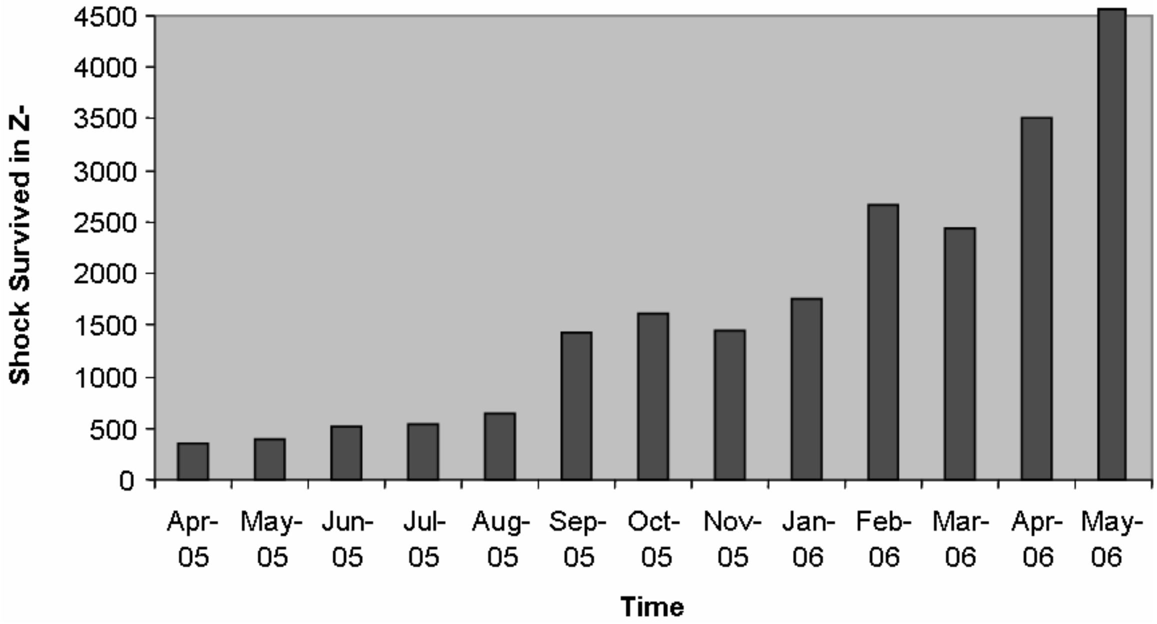

Figure 11. History of shock performance. Current shock performance, as of December 2006, exceeds 8,000 g.

Another important aspect of performance, particularly in the cell phone application, is shock survivability. Cell phones are expected to work even after repeated drops by its user. While a digital camera would most likely stop working after dropping the camera on the floor even once, a camera in a cell phone is expected to work after dropping the cell phone 36 times onto concrete. This requirement imposes severe shock survivability requirements for the digital cameras in cell phones. Figure 11 shows the time history of the shock performance of the MEMS digital camera from April of 2005 to May of 2006, which illustrates the large amount of development that was required to reach an acceptable shock survivability. As of December 2006, the shock survivability of the MEMS digital camera is 8,000 g. Figure 9 also shows the performance of the camera before and after dropping the camera inside of a cell phone 36 times onto concrete. As this test illustrates, the performance of the camera remains practically unchanged.

Table 1. Typical results for performance of the 2MP MEMS digital camera over temperature.

Temperature (Celsius)	25	0	-10	-20	25	40	60	75	Maximum Difference
Lens Focus Position (um) +/- 4um	261	258	254	248	256	248	245	241	20 um +/- 6
MTF50 (Center) +/- 5 LW/PH	686	683	678	676	683	661	662	682	25 LW/PH +/- 7

It is also required for the camera to operate over temperature without degradation in optical performance. Using our custom temperature testing system, we are able to evaluate the optical performance of a camera over a broad temperature range. In this system, the camera takes pictures of a resolution target that is 30 cm away inside of a temperature chamber. Table 1 illustrates typical results of testing a 2 MP MEMS digital camera from -20 Celsius to 75 Celsius. The lens position was measured in micrometers and indicates the position of the lens required to focus onto the target. The MTF50 represents the frequency, in line widths per photograph (LW/PH), at which the MTF drops to 50%, and represents the resolution of the camera without any image processing. Image processing of the raw image tends to improve the resolution, but is not desirable for this test as it may obscure important effects of temperature. As can be seen from the data, the maximum change in the position of the lens for best focus is 20 micrometers and the maximum change in resolution is 25 LW/PH. Overall, the performance of the MEMS digital camera is very stable over temperature.

The use of a MEMS stage is largely responsible for the high degree of reliability of the MEMS digital camera. Silicon is a very good mechanical material, having a strength that is about 10 times larger than steel (4-6 GPa vs 400-600 MPa). Silicon is also a very pure material, so its properties are highly reproducible and predictable. Finally, since single crystal is not plastically deformable and has no built in stress, the performance of the stage remains unchanged after many operating cycles or thermal cycling from -40 C to 85 C. For example, our first demonstration system has been running continuously for over 1 year at realistic actuation frequencies and has accumulated in excess of 22 million cycles without any degradation in performance.

4. CONCLUSION

MEMS technology offers a bright future for digital cameras in cell phones and promises to enable the reduction in size of digital cameras without compromising on the optical performance. In this paper, we presented the first MEMS digital camera for use in cell phones.

5. ACKNOWLEDGMENTS

The authors gratefully acknowledge the many contributions of fellow Siimpel engineers in the practical realization of the MEMS-based digital camera. We also acknowledge the support of the Advanced Technology Program (ATP) for supporting the early development of the technology, and the continued support of our investors.

6. REFERENCES

This technology is protected by US Patents numbers: US7,113,688; US6,850,675; US6,674,585; US6,661,962; US6,661,955; and other US and International Patents pending.