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OPTO-MECHANICAL EFFECT IN CHALCOGENIDE GLASSES

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The opto-mechanical effect observed in amorphous chalcogenide films deposited onto clamped STM cantilevers [1] has been investigated. In this, bandgap light, incident on the chalcogenide film and linearly polarized either parallel or perpendicular to the cantilever axis, reversibly causes respectively either a contraction or an expansion of the chalcogenide layer, resulting in an optically-actuated displacement of the free end of the clamped cantilever. This effect is electronic, not thermal, in origin, and is believed to be caused by the same photo-induced structural rearrangements that are responsible for the optically induced optical anisotropy observed in chalcogenide glasses. Possible applications of this new all-optical actuation for optical switching will be discussed.

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1. Introduction

It is becoming apparent that the next generation of telecom networks, fibre sensors, optical switches or, in the extreme case, also data manipulation, will depend on all-optical technology. At present, one of the major bottlenecks to achieve full photon compatibility in present-day devices is the lack of a suitable all-optical switching capability. Various micro-electro-opto-mechanical systems (MEOMS) are utilised to achieve even better performance; however, ultimately these cannot compete in the long term with all-optical technology. Another issue, distant, but nevertheless progressing, is nanotechnology. It is well recognized that, if nanotechnology is to succeed, our ability to grip, position and release structures on the atomic scale has to improve greatly, not just in terms of precision but, and perhaps more importantly, in terms of scalability and vastly parallel processing. It appears that one of the key factors in the improvement of such future 'SMART' devices, is the mechanical actuation. At present, only a limited number of actuators with sufficient accuracy are available on the market, e.g. using piezoelectric or photostrictive actuation, but they lack sufficient tool-holding capability, as well as being too large and not easily miniaturisable to be made into large arrays of independent actuators.

One of the emerging new technologies with the promise of bridging the gap between nanotechnology and the macroscopic world is opto-mechanical actuation. An anisotropic mechanical effect induced by polarized light was first reported by Krecmer et al. [1]. They showed that, upon irradiation with polarized light, a thin amorphous film of $As_{50}Se_{50}$ deposited on a cantilever, exhibits reversible nanocontraction parallel to the direction of the electric vector of the light and nanodilatation along the axis orthogonal to the electric vector of the light, and a direct correlation of this opto-mechanical effect with the reversible photoinduced optical dichroism was observed. Measurements were made using a cantilever (consisting of an amorphous $As_{50}Se_{50}$ film, 250 nm thick, deposited on a silicon nitride V-shaped AFM cantilever 200 μm long and 0.6 μm thick), which was found to bend reversibly either up or down by up to about $\pm 1 \mu m$ upon illumination with polarized light (Fig.).

2. Experimental

2.1. Principle

The opto-mechanical effect in chalcogenide glasses (ChG) is, in principle, linked with the well-known phenomenon of photoinduced optical anisotropy [1], where polarized light can cause, in a

previously isotropic chalcogenide bulk or film sample, preferential absorption (and reflection) of the inducing (linearly polarized) light.

Irradiation with polarized light oriented along the axis of the cantilever (the y-axis, E_y) led to the deflection of the cantilever in the +z direction. The opposite effect, i.e. bending of the cantilever in the -z direction was observed when the light was polarized orthogonally to the direction of the cantilever axis (along the x-axis, E_x) (Fig. 1).

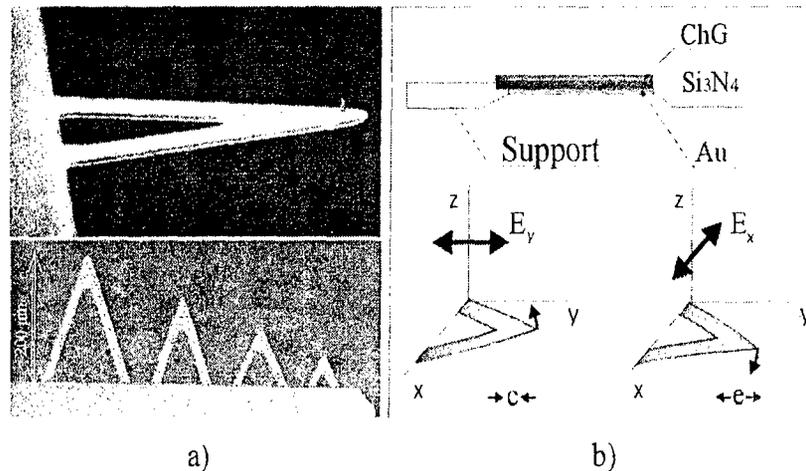


Fig. 1a) Atomic force microscope cantilevers used for the optical-actuation experiments. b) A schematic illustration showing the general structure of the samples used in our experiments and the contraction/expansion of the cantilevers. At the top is a schematic illustration of the gold-Si₃N₄-ChG sandwich. The light in this case is incident on the cantilever from +z direction and its electric vector is polarized either in the y-direction or the x-direction.

The origin of this mechanical polarization effect is not known. Whereas amorphous materials are by nature generally isotropic, some can be made anisotropic by simply illuminating them with polarized light (resulting in them becoming either dichroic or birefringent). The phenomenon of optical anisotropy was first observed in chalcogenide glasses by Zhdanov et al. [2], and the mechanism has since been studied extensively. We can suppose that the microscopic origin of the effect arises from some (anisotropic) structural elements that can be aligned by linearly polarized light. The main problem still remaining to be solved is to identify these structural elements. Krecmer et al. [1] suppose that absorption of polarized light will occur when the E vector of the polarised light is parallel to the main axis of the triangle consisting of a triplet of As-Se-As atoms. After excitation of a lone-pair electron (LP), an electron-hole pair is created, which no longer has the spatial symmetry of the LP orbital, and because of the change of interatomic potential, this leads to a displacement swing of the chalcogen atom. The cooperative swing of many atoms in one direction is then supposed to cause both the mechanical and optical anisotropy [1]. However, there is barely any agreement between different research groups regarding the microscopic structures that are responsible for the optically-induced anisotropy.

2.2. Actuation

Actuators perform useful work on the environment in response to a command or a control signal. The amount of work that they perform and the energy expenditure that they require to do the desired work depend drastically on the method of actuation. These methods can be divided into six categories: electrical, magnetic, thermal/phase, mechanical/acoustic, chemical/biological and optical [3].

Systems, which utilize either an electrical or an optical transduction technique, can be classified as either MEMS (micro-electro-mechanical system) or MOMS (micro-opto-mechanical system). MEMS actuators can employ either piezoelectric, electrothermal or electrostatic means in order to provide the necessary driving force. In contrast to this, MOMS sensing devices may operate

by monitoring either the intensity of light or its wavelength, polarization, or phase. MOMS actuators can utilize either the photothermal effect, the photomechanical effect or radiation pressure [4].

Optical actuation is divided into direct and indirect optical methods. Direct optical methods use light to interact with the active parts of the actuator and cause actuation. Indirect optical methods take advantage of the heating power of the light or its ability to generate an electrical current or to change the resistivity of photo-responsive materials. Several practical benefits distinguish direct optical methods from radiative-thermal processes. Direct optical processes can be much faster than indirect ones, and they can take place at much lower light powers and they permit greater simplicity, versatility and parallelism of the controller.

An interesting feature of both types of optical actuators is that they can be directly interfaced with fibre optics or other forms of waveguides, such as integrated optics [5]. This feature makes optical actuators ideal candidates for smart structures [6], where many actuators are multiplexed (in time or frequency) and located over large areas.

We have discovered a new type of direct optical actuator that uses reversible nanocontraction and dilatation in chalcogenide glasses induced by polarized light [1]. This optomechanical effect was demonstrated on Si_3N_4 V-shaped microcantilevers coated with amorphous $\text{As}_{50}\text{Se}_{50}$ (see Fig.).

There are several features that make the smart technology of optical actuation involving chalcogenide materials much better than other kinds of actuation:

The opto-mechanical effect is highly reversible.

The effect is wavelength-selective (the maximum response is for light having an energy comparable to the chalcogenide bandgap).

Since light is used as the stimulus, no electricity is needed as in piezoelectric devices. Optical actuators can therefore be used in hazardous environments (e.g. flammable atmospheres) where the use of high voltages (as for piezoelectric devices) would be unsafe.

It is potentially cheap.

Optical actuators lend themselves to miniaturisation, and large arrays of independent cantilevers can be envisaged for applications requiring massively parallel processing.

2.3. Measuring set-up

A vibrational-free optical workplace, together with a temperature stable environment, is the key factor for measurement on nanometer scales. The cantilever is illuminated (from the side coated with the chalcogenide film) with polarized light from laser a He-Ne laser (10 mW). The direction of polarization is adjustable between 0-90 degrees by a $\lambda/2$ waveplate for 632.8 nm. The displacement of the cantilever is detected by measuring the deflection of a laser beam focused on the apex of the cantilever and reflected from the gold surface coating of the other surface of the cantilever. As chalcogenide glasses are sensitive to visible light illumination, the system incorporates a low-power (50 μW) modulated laser diode (655 nm, 119 Hz) as the measuring beam, deflecting from the gold surface onto a position-sensitive quadruple photodiode. The signal is fed into a digital lock-in analyser for enhanced sensitivity of the measurement. Fig. 1 shows a schematic of the measuring apparatus.

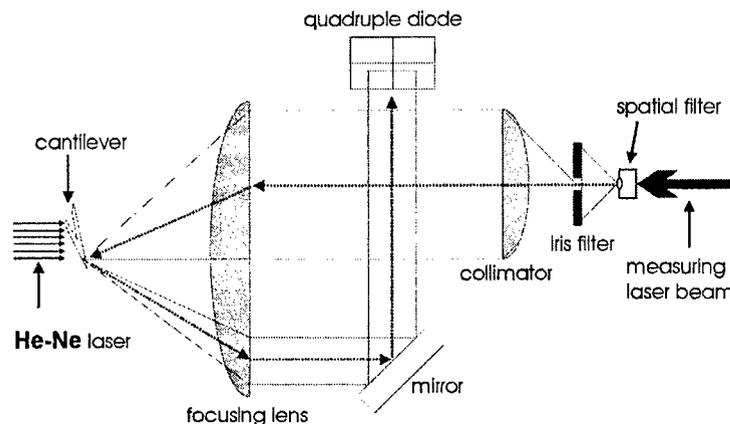


Fig. 1. Illustration of set-up for measurement of the opto-mechanical effect on cantilevers.

3. Results and discussion

The cantilever (consisting of an amorphous $\text{As}_{50}\text{Se}_{50}$ film, 260 nm thick, deposited on a silicon nitride V-shaped AFM cantilever 200 μm long and 0.6 μm thick) bends reversibly during illumination with a He-Ne laser with different directions of polarization, parallel (\parallel) or perpendicular (\perp) to the cantilever. The polarization-dependent signal is superimposed on a photoinduced scalar expansion, which is shown in Fig. 3a) after switching the incident laser power off. This observation is in accordance with previous measurements [7], and can, in principle, be composed of both a scalar photoexpansion and differential thermal expansion of the glass matrix and the substrate. Fig. 2b) shows the reversibility of the cantilever displacement alternating with change of direction of the laser polarization. This result is in agreement with those carried out earlier on a different apparatus [1].

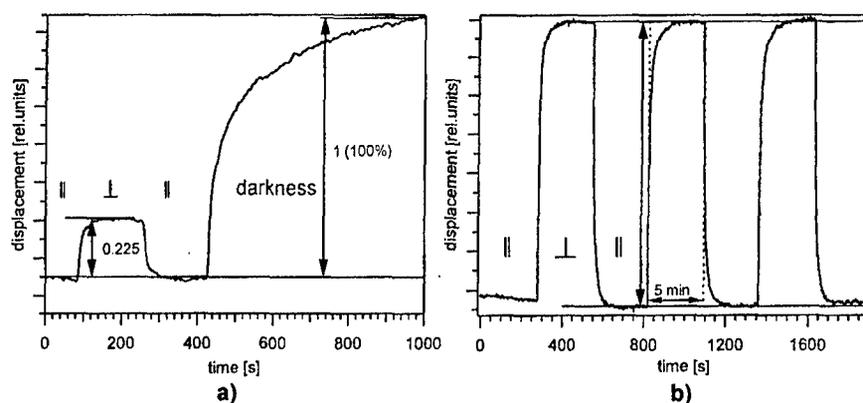


Fig. 2. The changes in relative displacement of the cantilever covered with a 260 nm thick $\text{As}_{50}\text{Se}_{50}$ film illuminated with a $30 \text{ mW}\cdot\text{cm}^{-2}$ He-Ne laser. a) The cantilever relaxes to its equilibrium position after the incident laser is switched off. b) Reproducibility of the relative displacement after several polarization plane alternations.

The response of the cantilever depends on the power density of the illuminating laser beam. The experiment was performed with a He-Ne laser with a maximum output power of $200 \text{ mW}\cdot\text{cm}^{-2}$. The influence of the laser power on the optomechanical displacement is shown in Fig. 3. The time constant of the fastest curve is of the order of 6-10 s for $200 \text{ mW}\cdot\text{cm}^{-2}$ input power of He-Ne beam and the given chalcogenide glass/cantilever system. Note that this value is system specific and other systems are now being studied to decrease this time constant to the millisecond range.

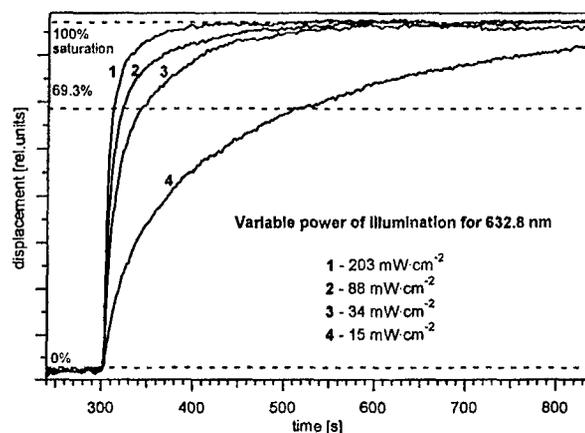


Fig. 3. Variable illumination power causes a certain level of saturation of displacement to be reached in different times. The laser power has been changed neutral density filters.

The illuminating laser power is not the only influence on the bending capabilities of the cantilevers; there is, of course, a size and shape dependency as well. These properties are closely related to different force constants of the cantilevers. This behaviour is shown in Fig. 4, where

cantilevers with various force constants 1) $0.03 \text{ N}\cdot\text{m}^{-1}$, 2) $0.06 \text{ N}\cdot\text{m}^{-1}$, 3) $0.4 \text{ N}\cdot\text{m}^{-1}$, 4) $0.2 \text{ N}\cdot\text{m}^{-1}$ covered with the same 260 nm thick $\text{As}_{50}\text{Se}_{50}$ film have been measured under the same conditions. As expected, the biggest and fastest response has been found for the cantilever with the smallest force constant (curve 1). However, it is also shown that increasing the force constant by a factor of two (curve 2) does not significantly change the relative cantilever displacement or the kinetics. Also increasing the force constant by more than an order of magnitude (i.e. curve 1 vs. curve 3) has a relatively small influence on the displacement (note the lengths of cantilevers 3 and 4 is half that of 1 and 2). These observations suggest the existence of a relatively very strong force constant of the chalcogenide film, and that even thinner chalcogenide films could be used to achieve similar kinetics and displacements. This property is currently under investigation.

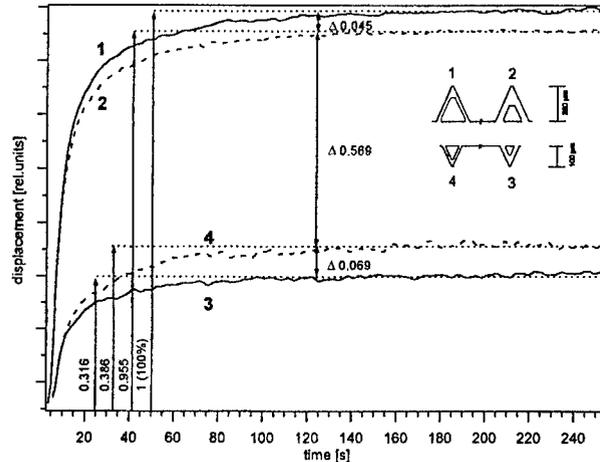


Fig. 4. The effect of cantilever size. The response of the cantilever depends on its force constant, which varies with size and shape of each cantilever 1) $0.03 \text{ N}\cdot\text{m}^{-1}$, 2) $0.06 \text{ N}\cdot\text{m}^{-1}$, 3) $0.4 \text{ N}\cdot\text{m}^{-1}$, 4) $0.2 \text{ N}\cdot\text{m}^{-1}$.

Until now we have been concerned with properties of the cantilever illuminated with the laser polarized either parallel or perpendicular to its main axis. However, for the phenomenon to be utilized in micromanipulators, we have investigated the effect of the cantilever displacement of intermediate angles between the light polarization and cantilever axes. Fig. 5 shows that it is possible to drive the cantilever, not only between two extremes, but also its bending can be regulated in intermediate positions simply by changing the angle of polarized incident light relative to the cantilever axis. This property can be very useful in optical-mechanical manipulation (MOMS) applications (e.g. optical tweezers or multi-way optical switches).

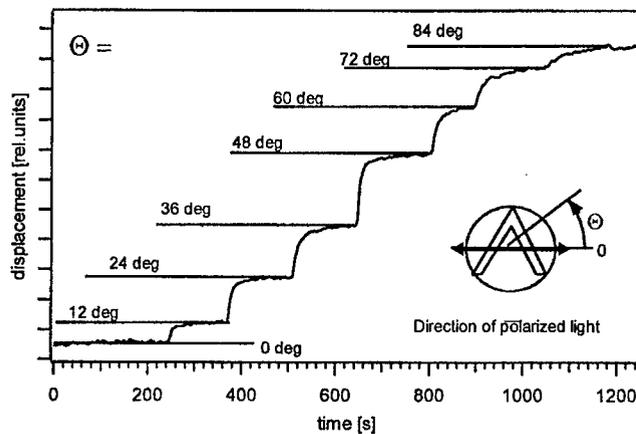


Fig. 5. Dependence of cantilever displacement on angle of polarization of the laser light. The angle of polarization has been changed by rotation of a $\lambda/2$ waveplate.

4. Conclusions

One of the major advantages of the opto-mechanical effect in chalcogenide glasses is the direct light-to-mechanical effect coupling without the need for other external sources. In this paper, we have demonstrated the potential of this effect for it to be used in optical switching and micromanipulators. However, if any meaningful structures are to be built, a more detailed analysis of the mechanical characteristics of the composite cantilever with respect to temperature expansion of both materials, differences in modulus, various types of designs, scaling behaviour etc., together with wavelength, temperature, intensity and compositional dependencies need to be investigated. These are currently under investigation.

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