# Transparent, Conducting Films Based on Metal/Dielectric Photonic Band Gaps

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ABSTRACT

A transparent conductor has been developed based on one-dimensional metal/dielectric photonic band gap structures. Laminated metal/dielectric filters containing 100nm of silver have been fabricated with >50% transmittance. Applications for transparent, conducting films include antennas embedded in windshields, electrodes on flat panel displays, electromagnetic shielding, and solar window panes.

SUMMARY

Since metals are highly reflective, it was thought that a photonic band gap crystal containing alternating layers of metal and dielectric would not exhibit a photonic band structure. It was expected that all electromagnetic radiation would be reflected or absorbed and none would be transmitted. In fact, a single silver film 40nm thick transmits only 7% of the incident radiation for wavelengths in the visible. However, resonant tunnelling through multiple metal films can enhance the transmission by several orders of magnitude. The periodic nature of the metal/dielectric lattice causes the light to propagate through the metal layers with extremely low loss. A related device exists in electronics, the resonant tunnel diode which contains a single barrier that the electrons tunnel through. An interesting feature of the resonant tunnelling process in a metal/dielectric photonic band gap crystal is that the tunnelling efficiency is very low for a single metal layer, enhanced tunnelling is only evident if two or more metal/dielectric periods are present. A surprising fact is that the transmission through the metal/dielectric photonic band crystal may actually increase as more metal layers are deposited. In addition, the center wavelength, width, and sharpness of the transparency window for the metal/dielectric photonic band gap crystal is adjustable and generally dependent on the thickness and the number of the metal/dielectric layers. Perhaps the most unique feature of the transparent metal is the ability to have a single pass band and block all other radiation from static fields to soft X-rays. This remarkable property is a result of the highly dispersive nature of metals.

Several metal/dielectric photonic band crystals were grown to demonstrate the new technology. In one case, a photonic band crystal consisting of a 5 period lattice of silver and magnesium fluoride was grown containing a total metal thickness of 150nm. This is more than 10 optical skin depths of metal and will serve to illustrate the fact that resonant tunnelling can greatly enhance the transmittance. The sample was grown in a standard thin-film thermal evaporator with dual sources. Corning 2947 glass, 2.5cm by 7.5cm was used as the transparent substrate. The substrate was not temperature controlled during the growth.

Instead of growing a sample with uniform periodicity as in our earlier work[1], the silver layers had a chirp in the thickness. The chirp serves to smooth out oscillations in the

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transmittance spectrum. Starting from the substrate, the silver layer thicknesses were 20nm, 35nm, 40nm, 35nm, 20nm, respectively. The magnesium fluoride layers were all 145nm thick except for the final top layer which was 75nm thick. The thinner topmost magnesium fluoride layer serves as an anti-reflection coating and enhances the transmittance by 10% compared with a layer 145nm thick. The layer thicknesses were measured in situ by a quartz crystal thickness monitor. The thickness monitor was calibrated by profilometry measurements as well as optical transmittance measurements.

Essentially, the sample consists of four coupled Fabry-Perot cavities. Since each individual metal layer is nearly three optical skin depths thick, the cavities are weakly coupled and nearly degenerate. The result will be a relatively narrow transmission band, 100nm wide. We have shown previously[2], that by using thinner metal layers, 10nm thick, the cavities are strongly coupled which removes the degeneracy. In that case, a 400nm wide transmission band was obtained across the visible spectrum with 70% transmittance.

The measured transmittance of the chirped sample shows a 100nm wide pass band centered at 530nm with a maximum transmittance of 50%. In the pass band, the transmittance of the metal/dielectric photonic band sample is 17,000 time greater than for a single silver film containing the same amount of silver, 150nm. The measured transmittance is in good agreement with theoretical calculations based on the matrix transfer method. A transmission resonance at a wavelength of 330nm is near the plasma frequency for silver and is not due to the photonic band geometry. At frequencies above the plasma frequency, the metal should be transparent. However, interband transitions lead to absorption and in this region metals behave more like a lossy dielectric. Therefore, any other pass bands expected at higher frequencies for lossless materials are removed due to interband transitions. We note that the transmission resonance at 330nm can be removed without significantly changing the pass band at 500nm by replacing one of the silver layers with gold which has a slightly lower plasma frequency.

An unusual feature of the transmittance spectrum is that the pass band shuts-off after 600nm. In ordinary dielectric/dielectric photonic band gaps, the pass band extends all the way to static fields. In metal/dielectric band gaps, the pass band closes due to the highly dispersive nature of metals. The result can be a single pass band with stop bands extending down to static fields and soft X-rays.

Microwave transmission measurements were performed from 8-20GHz. As expected, the microwave power transmitted through the sample was below the noise floor for the measurement apparatus, -35dB. To compare the shielding capabilities of metal/dielectric photonic band structures with the industry standard for transparent conductive films, indium tin oxide (ITO), another measurement was performed with commercially available ITO. The ITO reduced the transmitted power by only -3dB.

Another important property of the sample is the electrical sheet resistance. Sheet resistivities for ITO range from 5-100ohm/sq. Measurements on metal/dielectric photonic band samples showed that the sheet resistance is equal to the resistivity of bulk silver divided by the total metal film thickness. This means that a metal/dielectric photonic band sample containing a total of only 100nm of silver will have a sheet resistance <0.2ohm/sq. It was determined that the silver layers in the silver/magnesium fluoride samples were in electrical contact, probably as a result of pinhole defects. It would also be possible to use other materials between the metal layers that are slightly conducting to establish contact between metal films.

In conclusion, metal/dielectric photonic band gap provide highly conductive, transparent films for sensor protection, UV protective films, embedded antennas, electromagnetic shielding and thermal management in heat reflecting windows.

1) M.J. Bloemer and M. Scalora, Appl. Phys. Lett. 72, 1676(1998).
2) M. Scalora, M.J. Bloemer, A. Manka, J. Dowling, and C. Bowden, J. Appl. Phys. 83, 1 (1998).