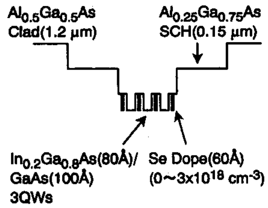
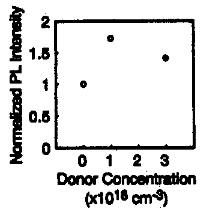
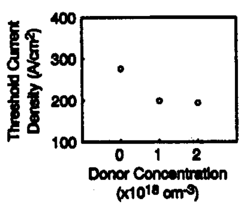


JThC5 Fig. 1 Schematic band structure of active region employing *n*-type modulation doping is shown. Se is doped as a donor around the center of GaAs barriers.



JThC5 Fig. 2 Normalized photoluminescence (PL) intensities against doping concentrations are displayed. The PL intensities from doped quantum wells are stronger than those from undoped ones.



JThC5 Fig. 3 Characteristics of threshold current density versus doping concentrations are summarized. The threshold current density as low as 200 A/cm^2 is obtained for a 1×10^{18} cm^{-3} doped laser.

InGaAs/AlGaAs QW vertical-cavity surface-emitting lasers (VCSELs) have been studied for optical interconnection because of their possibility of ultra low power consumption.[2,3] Much lower threshold VCSELs can be expected by introducing the *n*-type modulation doping technique reported here. From the above data, we can estimate the threshold current of a single QW VCSEL having 3 μm-core fabricated by native oxidation method, and then the expected threshold current value will be lower than 10 μA, when the cavity loss is assumed to be 15 cm^{-1}.

In summary, we grew *n*-type modulation doped InGaAs/AlGaAs QWs into the barriers and observed enhanced PL intensities. We fabricated edge-emitting lasers using the QWs and achieved the reduction of the threshold current density for the first time. The obtained result shows that the *n*-type modulation doping could improve the laser performance in terms of reduction of turn-on delay time, resulting in the possibility of future parallel optical transmission system.

1. K. Uomi, Jpn J. Appl. Phys. **29**, 81–87 (1990).
2. Y. Hayashi *et al.*, Electron. Lett. **31**, 560–562 (1995).
3. G. M. Yang *et al.*, CLEO '95 Digest CPD4-1 (1995).

CThJ — 10:30 am — Salon F

Photonic Bandgap Materials

Leslie A. Kolodziejski, *Massachusetts Institute of Technology, Presider*

CThJ1 (Invited) — **10:30 am**

3-D metallic photonic bandgap structures

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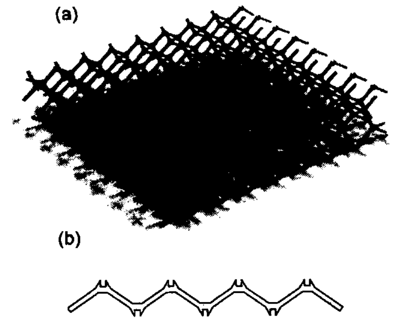
Most of the work on photonic bandgap materials to date has focused on dielectric structures because of their low loss at optical wavelengths. While metals are not suitable for use in this range, they find many applications at microwave frequencies. We believe we have constructed the first 3-D metallic photonic bandgap structure in a geometry resembling covalently bonded diamond.

The structure we have chosen consists of an interconnected wire mesh in the form of a diamond lattice. The "atoms" are geometrical points in space, and the valence bonds connecting those points are copper wires, 1-cm long. A photograph of our wire mesh structure is shown in Fig. 1, together with a detailed view of the copper wire strips, which snap together to make diamond geometry.

Our experiments consisted of microwave transmission measurements through the 3-D wire mesh structure, as a function of incidence angle and frequency. As expected, narrow forbidden gaps are observed centered at frequencies ν_0, corresponding to the spatial periodicity of the wires. However, a new gap is also observed, which extends from zero frequency up to a finite frequency, ν_p. We observe in our geometry that ν_p is approximately one-half of ν_0. We regard ν_p as being analogous to a type of plasma frequency associated with the motion of electrons in the continuous, interconnected, wire network. Alternately, it may be considered as a 3-D cut-off frequency for wavelengths too large to fit between the rows of wires.

Given that microwave-lengths are rather large, combined with the need for multiple mesh periods to form a 3-D crystal, it is preferable to design metallic photonic crystal structures where electromagnetic waves penetrate a wire mesh whose spacing a <<λ, the vacuum wavelength. This condition defines a *new and different regime* of photonic crystals. In the new regime a <<λ, the crystal structures are actually effective media, described by a frequency-dependent dielectric constant, ε(ω), rather than the full 3-D wave vector dependence, $\varepsilon(\vec{k})$, of a true photonic crystal. Nevertheless, such effective media can have many unusual properties, including particularly a negative, predominantly real, dielectric constant at microwave frequencies, which would otherwise be difficult to find among solid metals. Furthermore, metallic photonic crystals appear to support longitudinally polarized plane waves in addition to the transverse waves.



CThJ1 Fig. 1 (a) A perspective photograph of our diamond geometry, 3-D, wire mesh photonic crystal. The individual wires play the role of "valence bonds" connecting the "atoms," which are merely geometrical points in space. The wires have a 1.25-mm square cross-section, and are 1-cm long. (b) A detailed view of the copper wire strips that snap together to make diamond structure.

The basic approach toward creating a penetrable medium in which a <<λ, is to introduce an impurity band within the low-frequency forbidden gap, below ν_p. Defects in our structure are created by selectively cutting wires, resulting in modes within the forbidden gap, which appear as a narrow peak in the transmission spectrum. Two or more closely spaced defects are found to interact with each other to produce split resonances, resembling the interaction of energy levels in chemical molecules.

The effective medium limit, a <<λ, of a 3-D wire mesh photonic crystal has many possible applications including antenna structures. Passive filter "windows," or frequency selective radomes, quasi-optical amplifying structures, and stealthy surfaces.

This work is supported by the Army Research Office and the National Science Foundation.