Surface-Plasmon Quantum Cascade Microlasers With Highly Deformed Resonators

R. Colombelli, *Member, IEEE*, C. Gmachl, A. M. Sergent, D. L. Sivco, Evgenii E. Narimanov, *Senior Member, IEEE*, Viktor A. Podolskiy, A. Y. Cho, *Fellow, IEEE*, and F. Capasso, *Fellow, IEEE*

***Abstract*—We report the demonstration of surface-plasmon microcylinder quantum cascade lasers with circular and deformed resonators. An improved self-alignment fabrication technique was developed that allows the use of wet etching, necessary to achieve smooth and clean surfaces, in combination with the deposition of the surface-plasmon-carrying metal layer up to the very edge of the resonator, where the optical mode is mostly located. The diameter of the microcylinders ranges from 75 to 180 μm while their deformation coefficient ε ranges from $\varepsilon = 0$ to $\varepsilon = 0.32$. Circular microcylinder lasers show a reduction of $\sim$50% of the threshold current density with respect to devices with standard ridge-waveguide resonators. On the other hand, highly deformed microcylinder lasers exhibit a complex mode structure, suggesting the onset of chaotic behavior.**

***Index Terms*—Microdisk lasers, microlasers, midinfrared, unipolar devices.**

RECENT advances in the development of quantum cascade (QC) lasers [1] dramatically extended their operating wavelengths well into the far-infrared (IR) and terahertz ranges [2]–[4]. This success was prompted not only by the use of advanced quantum designs, but also by the innovative use of waveguides based on surface-plasmon polaritons, originally demonstrated in the mid-*IR* [5]. The availability of very long wavelengths makes the development of QC lasers using microdisk or microcylinder resonators especially interesting. The prospect of very low current thresholds and single mode emission is a result of the miniaturized dimension of the cavity and the intrinsically low out-coupling losses, due to the advantageous ratio between the length-scale of the sidewalls' roughness and the operating wavelength. Rayleigh scattering of the light at the sidewalls is reduced, with beneficial effects on the threshold current density. As for the output power, it was shown by Gmachl *et al.* [6] that it can be increased by even three orders of magnitude if a clever deformation is added to the cavity shape. In fact, for a limited range of deformations, so-called *bowtie modes* exist that exhibit a high Q factor and at the same time can more easily escape thanks to refractive effects. Finally, the longer wavelength allows the achievement of high $Q/V_{\rm eff}$ factors without fabricating prohibitive small cavities, where Q is the quality factor of the cavity and $V_{\rm eff}$ is the effective mode volume.

In surface-plasmon-based QC lasers, the optical mode is a TM polarized electromagnetic wave bound at the top metal-semiconductor interface that decays exponentially away from the latter. The top metal is, therefore, an essential part of the waveguide. Since whispering gallery (WG) optical modes are located mostly at the periphery of the disc [7], it is essential that the top metal contact, and thus the waveguide, extends to the very edge of the microcylinders. It is possible to fulfill this requirement when the top contact is used as a metallic mask and the semiconductor is etched via reactive ion etching. However, the use of dry- instead of wet-etching techniques constitutes a serious drawback since the surface roughness is more pronounced and the achievable Q factors are smaller.

In this paper, we report the demonstration of surface-plasmon microcylinder QC lasers. The devices have been realized with an improved fabrication technique that allows us to combine the advantages of wet etching with the requirement of a metal contact/waveguide extending to the edge of the resonator.

The laser structures have been grown by molecular-beam epitaxy using $In_{0.53}Al_{0.47}As/Al_{0.48}In_{0.52}As$ lattice matched to a low-doped ($n \approx 2 \times 10^{17}$ cm^{-3}) InP substrate. The active regions of the lasers are based on interminiband transitions in chirped undoped superlattices. They have been designed for the longest possible emission wavelengths compatible with the InGaAs/AlInAs material system, i.e., $\lambda \approx 17, 19, 21,$ and 24 μm [8]–[11]. The details of the growth are reported in [8]–[11]. Seventy-five active region/injector stages were grown for the $\lambda = 17, 21,$ and 24 μm lasers, while only 40 stages were grown for the $\lambda = 19$ μm laser [10].

The fabrication procedure is described in Fig. 1. The core improvement consists in using a double-layer mask (SiN and resist) in order to avoid a second lithography after the semiconductor etch and before the evaporation of the top metallic contacts. Such a second lithography would not allow a perfect match for the shape of the etched microcylinders, due to unavoidable undercut effects and to limits to the achievable alignment precision. After the deposition of a 300-nm-thick SiN layer, resist is patterned with optical lithography [Fig. 1(a) and (b)]. The patterns (circular or stadium-shaped) are then transferred to the SiN with reactive ion etching [Fig. 1(c)], and the SiN-resist double-layer is used as a mask for the semiconductor

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R. Colombelli is with the Institut d'Electronique Fondamentale-Bât.220, Université Paris-Sud, 91405 Orsay, France (e-mail: colombel@ief.u-psud.fr).

C. Gmachl and E. E. Narimanov are with the Department of Electrical Engineering and PRISM, Princeton University, Princeton, NJ 08544 USA.

A. M. Sergent, D. L. Sivco, and A. Y. Cho are with Bell Laboratories, Lucent Technologies, Murray Hill, NJ 07974 USA.

V. A. Podolskiy is with the Physics Department, Oregon State University, Corvallis, OR 97331 USA.

F. Capasso is with the Division of Engineering and Applied Sciences, Harvard University, Cambridge, MA 02138 USA.

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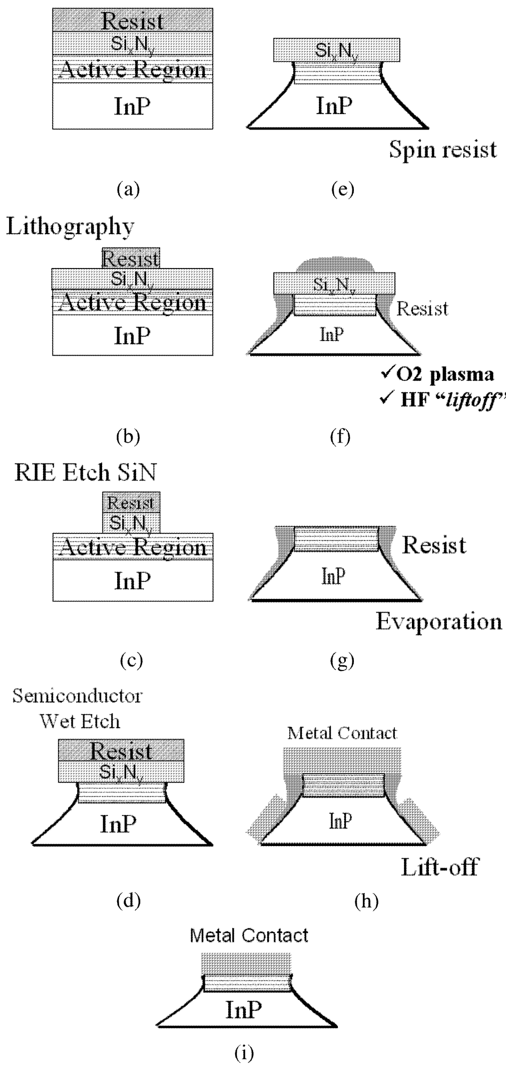

Fig. 1. Fabrication steps of the surface-plasmon microdisk QC lasers. (a) SiN and resist deposition. (b) Optical lithography. (c) Pattern transfer to the SiN with reactive ion etching. (d) Semiconductor wet etch. (e) Resist removal with acetone. (f) Spin coating at high spinner rotation speeds. (g) HF lift-off. (h) Top metal contact evaporation. (i) Acetone lift-off.

wet etch [Fig. 1(d)]. The resist is then removed with a solvent [Fig. 1(e)] and deposited again through spin-coating. Thanks to the sharp undercut of the SiN layer and to the surface adhesion forces, the resist assumes an unusual shape (see Figs. 1(f) and 2): It partially covers the top surface of the SiN mask, but it completely fills the space left by the undercut. Dipping the sample in HF acts as *lift-off*, etching away the sacrificial SiN layer and leaving the microcylinders' surfaces exposed, while the rest of the sample is still covered by resist. A top metal contact (Ti/Au, $100\ \text{Å}/2000\ \text{Å}$) is then evaporated, followed by a lift-off in acetone [Fig. 1(h) and (i)]. The results are shown in Fig. 3. Particularly Fig. 3(b) proves that the metal, and therefore the waveguide, covers the whole surface of the resonator.

After polishing and back-contact deposition, the samples were soldered with indium to a copper block and mounted in a cryogenically cooled micropositioner stage, where each device could be contacted individually with a microprobe. While all

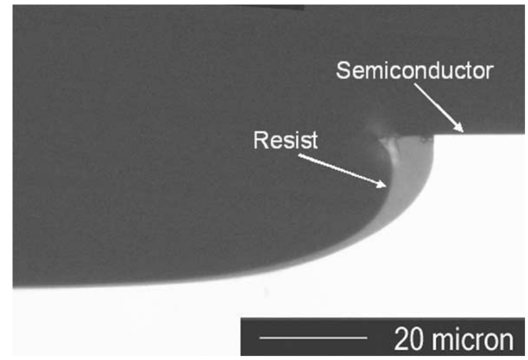

Fig. 2. Optical microscope image of a sample that was cleaved after the second resist deposition. The unusual shape of the resist is due, as stated in the text, to the semiconductor undercut in combination with the resist surface adhesion forces. It is worth noting the exceptional thickness ($\approx 10\ \mu$m) that the resist achieves in this circumstance.

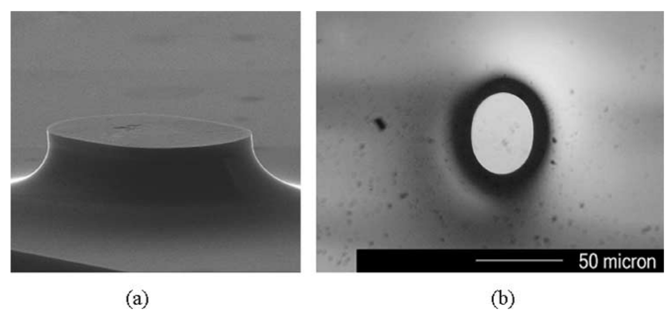

Fig. 3. (a) Scanning electron microscope (SEM) image of a fabricated device. (b) Top view of a device through an optical microscope. The top metallization extends up to the very edge of the microcylinder.

the lasers could operate in pulse mode, only the 19-μm laser achieved continuous wave (CW) operation. In this paper, we will concentrate on this latter set of devices.

Fig. 4(a) shows some selected laser spectra for an almost circular device operated at 10 K in CW. The threshold current density for this device was ≈ 1.5 kA/cm^2. This value should be compared to the value of 3.2 kA/cm^2, obtained from the same material processed as standard Fabry–Perot ridge resonators [10]. The resonator length was in that case 375 μm, which gives rise to high out-coupling losses. The dramatic reduction of the threshold current density—about 50%—is likely caused by two factors. In microcylinder lasers, the light circulates in the outer part of the disc. Since the light is confined by total internal reflection, there are only minute losses caused by evanescent leakage and scattering from surface roughness. This allows one to reduce the device dimensions, with beneficial effects on the heat dissipation for CW operation, without dramatically increasing the out-coupling losses. In addition, our fabrication technique is a one-step process. No SiN is deposited on the sidewalls for insulation, and no additional lithography is required after the semiconductor etch, thereby keeping the surface roughness and sidewalls' deterioration to a minimum. The Q factor of our resonator can be estimated in a straightforward manner. We can infer the out-coupling losses from the following expression for the threshold current density [12]: $J_{\rm th} = \frac{\alpha_w + \alpha_{\rm out}}{g\Gamma}$, where $\alpha_w = 62$ cm^{-1} are the material losses, $\alpha_{\rm out}$ are the

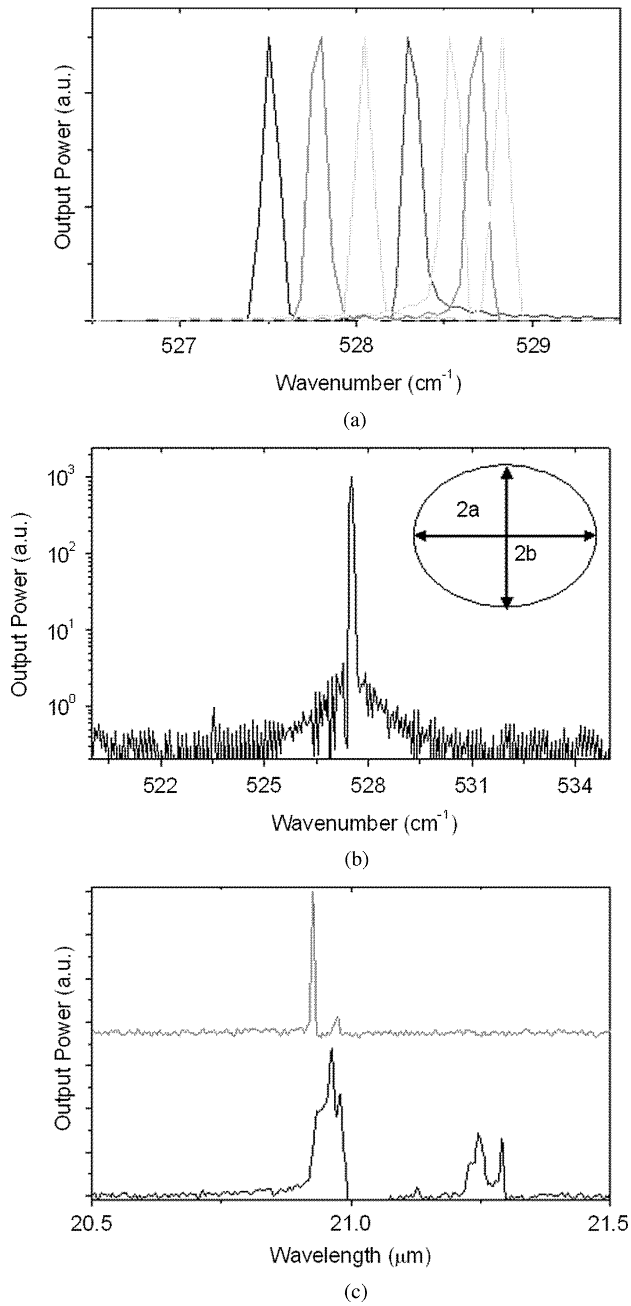

Fig. 4. (a) Selected laser spectra ($T = 10$ K) of an almost circular device (with major and minor axis of $a = 47.5$ μm and $b = 45$ μm, respectively, corresponding to $\varepsilon \approx 0.027$) for different injection currents (linear scale). The device was operated in CW, with injection currents of (right to left) 120, 130, 140, 160, 180, 200, and 220 mA, respectively. (b) A typical spectrum in logarithmic scale, showing a sideband suppression ratio of $\sim$25 dB. (c) Typical spectra for the $\lambda = 21$ μm laser, operating in pulsed mode, showing the presence of frequency chirping effects.

out-coupling losses, $\Gamma = 0.81$ is the mode confinement factor, and g is the material gain. Using the calculated values for g (= 58 cm/kA) and $\Gamma(= 0.81)$ [9], and the experimental value for $J_{\rm th}$ (= 1.5 kA/cm^2), we obtain $(\alpha_w + \alpha_{\rm out}) \approx 70$ cm^{-1}. In turn, this corresponds to $Q \approx 300$, using the following formula: $Q = \frac{2\pi \cdot n_{\rm eff}}{\lambda \cdot (\alpha_w + \alpha_{\rm out})}$ [12]. Since $\alpha_w \approx 62$ cm^{-1}, the Q factor of our resonator is limited mainly by the material losses. However, $Q \approx 300$ is a relatively high value for a $\lambda \approx 19$ μm laser [12], and it suggests that this approach is potentially very interesting in the THz range. As a matter of fact, in that wavelength range material losses have been shown to be $\approx$ 6–8 cm^{-1}. Even lower values, between 0.5 and 1 cm^{-1}, can be achieved when the device is operated in presence of a magnetic field [13], [14].

Recent theoretical work [15], [16] suggested that effects known from the field of nonlinear dynamics, such as chaos-assisted tunneling, could arise in highly deformed microresonators. The magnitude of these effects, which can reveal themselves as minute splittings of the laser lines for increased deformations, scales with the emission wavelength as λ/r, where r is the average radius of the microresonator [15], [16]. In addition, the deformation should be quadrupolar $((\varphi) \propto [1 + \varepsilon \cdot \cos(2\varphi)])$, flattened quadrupolar $(r(\varphi) \propto [1 + \varepsilon \cdot \cos(2\varphi)]^{1/2})$ [6], or an equivalent shape. Such a shape can be obtained with wet etching, starting from a stadium-shape resist pattern (i.e., two semicircles connected by a rectangle). Thanks to the smoothing action of the etchant, the straight sections gradually bend toward the curved parts, eventually rendering a (flattened) quadrupole shape [6]. It is worth noting that the (flattened) quadrupolar shape is difficult to obtain without wet etching, since it would require the use of a very-high-resolution laser (or even electron-beam) stepper.

We fabricated surface-plasmon QC microcylinder lasers with a flattened quadrupolar shape and several different deformation values (ranging from $\varepsilon = 0$ to $\varepsilon = 0.32$ using the $\lambda = 19$ μm material. The choice of the $\lambda = 19$ μm laser was motivated by its ability to operate in CW mode. Unwanted effects such as frequency chirping were therefore avoided, as well as the onset of transverse modes. On the contrary, these effects heavily affected the other lasers that could operate in pulsed mode only [see Fig. 4(c)].

Fig. 5 shows the mode chart (emission wavelength versus injected current) for several devices with different deformations. Except for a limited and initial current range, lasers are usually multimode. While for small deformations ($\varepsilon < 0.1$), the mode distribution can be roughly explained with a ray-optics approach, for high deformations several additional modes suddenly appear. On one hand, the complexity of the spectrum is real, since the lasers operate in CW. The exceptional number of modes observed cannot therefore be attributed, for instance, to changes of $n_{\rm eff}$ during time, since the devices are in steady state. On the other hand, the number and distribution of the observed modes could not conclusively be attributed to chaos-assisted tunneling effects. A third hypothesis invokes spatial inhomogeneity: Different modes could have spatial distributions that do not overlap. However, we observed mode-competition effects in some highly deformed devices, suggesting that the laser modes do actually spatially overlap.

We did not observe a monotonic increase in output power as a function of deformation, as reported in [6]. Instead, once a deformation was introduced, the power increased by a factor 10–90 (depending on the device set) with respect to an exactly circular device, and no trend was observed with deformation. The increase in output power observed in [6] is related to the onset of the bowtie mode and to the fact that with the given effective index of refraction strong outcoupling of light occurs,

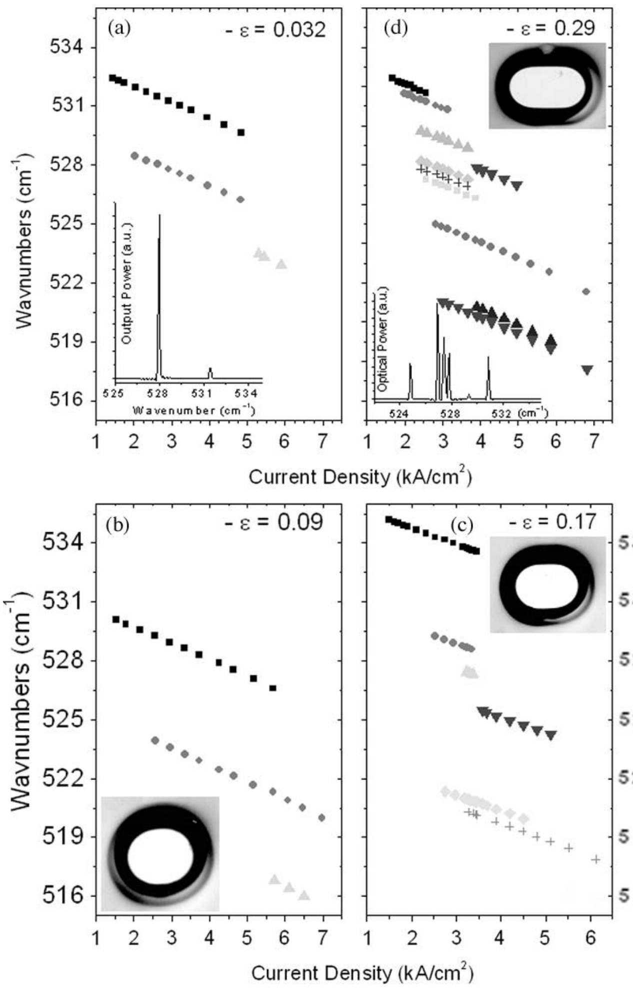

Fig. 5. Mode charts of four devices with different deformations. All the devices were operated in CW, at a temperature of 10 K. (a) $\varepsilon \approx 0.032$ ($a = 48$ μm, $b = 45$ μm). (b) $\varepsilon = 0.09$. (c) $\varepsilon = 0.17$. (d) $\varepsilon = 0.29$ ($a = 84$ μm, $b = 47$ μm). Insets: optical microimages of the measured devices and typical measured spectra.

as the condition for total internal reflection is met at angles very close to the bounce angles of the bowtie modes. In the devices discussed here, we believe that we did not excite the bowtie modes. We propose two explanations for that.

Our fabrication technique allowed us to deposit metal up to the very edge of the disk (see Fig. 3), contrary to what is usually the case for mid-IR microdisk QC lasers [6], [7], where the contact covers the center of the resonator only. The latter configuration might be more suited to excite a bowtie mode, since it preferentially pumps the center of the disk, introducing a clear competitive disadvantage for the WG modes, which are located mostly on the periphery of the disk. Instead, in our case, the current is injected uniformly on all the surface of the cavity: WG and bowtie modes now compete on equal grounds. The higher Q factors due to the longer wavelength (and especially the lower out-coupling losses) may have shifted the advantage from the bowtie to the WG modes. Second, the surface-plasmon modes have generally a larger effective refractive index; as a result, the angle of total internal reflection is smaller than that in [6], and as a result the bowtie modes are more lossy and are less likely to be excited.

In conclusion, we demonstrated pulsed and CW-operating microcylinder quantum cascade lasers with surface-plasmon waveguides at very long wavelengths ($\lambda \approx 17$–24 μm). An improved fabrication technique was developed that not only allows the fabrication of the devices with wet etching, but also succeeds in achieving microcavities with high Q factors. Results on highly deformed microresonators show anomalous spectral behaviors that, to date, could not be explained even by considering the onset of chaotic effects. In fact, the onset of a complex spectral behavior with increasing deformations may suggest that quantum chaos phenomena are becoming manifest. In order to exclude any effect related to spatial inhomogeneities, angle resolved measurements could be performed. This technique might allow one to infer the mode spatial distribution.

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R. Colombelli (M'00) was born in Modena, Italy, in 1971. He received the Laurea degree from the University of Pisa, Italy, and the Diploma and Ph.D. degrees from the Scuola Normale Superiore of Pisa, Italy, in 1995 and 1999, respectively, all in physics.

In 1999, he joined Bell Laboratories, Lucent Technologies, Murray Hill, NJ, as a Post-Doctoral Researcher, where his work was initially focused on quantum-cascade laser devices with special attention to long-wavelength emission. In 2001, he shifted his efforts on the application of photonic technology to unipolar devices. At the end of 2003, he joined CNRS, France, as Member of Research Staff at the Institut d'Electronique Fondamentale, Orsay, France. His current research activities focus on photonic-crystal quantum cascade lasers and midinfrared plasmonic devices.

Dr. Colombelli was awarded a EURYI European Young Investigator Award by the European Science Foundation in 2004. He is a member of the American Physical Society and the Optical Society of America.

C. Gmachl, photograph and biography not available at the time of publication.

A. M. Sergent has been with Bell Laboratories, Murray Hill, NJ, since July 1960. He has been in the semiconductor research area since the latter part of 1967. He has worked on the luminescence properties of the CdS and ZnSe materials systems and has also performed C-V, C-T, and deep level transient spectroscopy measurements on GaAs. Since the early 1990s, he has been involved in semiconductor laser research, working on the electroabsorption modulated laser and most recently with the quantum cascade laser. Most of his work in this endeavor revolves around the cleaving and mounting of the devices.

D. L. Sivco, photograph and biography not available at the time of publication.

E. Narimanov(M'01–SM'03) received the Ph.D. degree in semi-conductor physics from Moscow Institute of Physics and Technology, Moscow, Russia, in 1995.

From 1995 to 1998, he was Postdoctoral Associate in the Applied Physics Department of Yale University. In 1998, he joined the Theoretical Physics Department at Bell Laboratories, where he worked until 2000, when he became Assistant Professor in the Department of Electrical Engineering of Princeton University, Princeton, NJ.

V. Podolskiy received the Ph.D. degree in physics from New Mexico State University, Las Cruces, NM, in 2002.

He was Postdoctoral Associate at the Department of Electrical Engineering of Princeton University from 2002 till fall of 2004, when he joined Oregon State University, Corvallis, OR, as Assistant Professor of Physics.

A. Y. Cho (S'57–M'60–SM'79–F'81) was born in Beijing, China, in 1937. He received the B.S., M.S., and Ph.D. degrees in electrical engineering from the University of Illinois in 1960, 1961, and 1968, respectively.

He retired as the Semiconductor Research Vice President, Bell Laboratories, Lucent Technologies, Marray Hill, NJ, in 2000, and is now an Adjunct Semiconductor Research Vice President. He has made seminal contributions to materials science and physical electronics through his pioneering development of the molecular beam epitaxy (MBE) crystal growth process. He demonstrated that MBE could be used to prepare epitaxial films one atomic layer at a time, with exceptional control at atomic dimensions, and further showed that these films could be the basis of devices with never-before-realized electrical and optical properties. His work has bridged many disciplines ranging from fundamental quantum physics, through epitaxial crystal growth, to device fabrication and testing. He has authored over 590 papers in surface physics, crystal growth, and device physics and performance. He holds 75 patents on crystal growth and semiconductor devices related to MBE.

Dr. Cho is a recipient of the Electronics Division Award of the Electrochemical Society (1977); the American Physical Society International Prize for New Materials (1982); the IEEE Morris N. Liebmann Award (1982); the GaAs Symposium Award-Ford (1986); the Heinrich Welker Medal-Siemens (1986); the Solid State Science and Technology Medal of the Electrochemical Society (1987); the World Materials Congress Award of ASM International (1988); the Gaede–Langmuir Award of the American Vacuum Society (1988); the Industrial Research Institute Achievement Award of the Industrial Research Institute, Inc. (1988); the New Jersey Governor's Thomas Alva Edison Science Award (1990); the International Crystal Growth Award of the American Association for Crystal Growth (1990); the Asian American Corporate Achievement Award (1992); the AT&T Bell Labs Fellow Award (1992); the National Medal of Science, presented by President Clinton (1993); the Newcomb Cleveland Prize of the American Association for the Advancement of Science (1993–94); the IEEE Medal of Honor (1994); the Materials Research Society Von Hippel Award (1994); the Elliott Cresson Medal of the Franklin Institute (1995); the Computer and Communications Prize of the C & C Foundation, Japan (1995); the New Jersey Inventors Hall of Fame (1997); Honorary Doctor of Engineering, University of Illinois at Urbana-Champaign (1999); the Willis E. Lamb Medal for Laser Physics (2000); the University of Illinois Alumni Achievement Award (2000); the IEEE Third Millennium Medal (2000); the NASA Group Achievement Award (2000); Honorary Doctor of Science Degree, City University of Hong Kong (2000); Honorary Doctor of Science, Hong Kong Baptist University (2001); and Honorary Doctor of Engineering, Hong Kong University of Science and Technology (2003). He is a Fellow of the American Physical Society and the American Academy of Arts and Sciences. He is a member of the U.S. National Academy of Engineering (1985), the National Academy of Sciences (1985), the Third World Academia of Sciences (1987), the Academia Sinica (1990), the Chinese Academy of Sciences (1996), and the American Philosophical Society (1996).

F. Capasso (M'79–SM'85–F'87) received the Ph.D. degree in physics (*summa cum laude*) from the University of Rome, Italy, in 1973.

He was with Fondazione Ugo Bordoni as a Researcher from 1974 to 1976. At the end of that year, he joined Bell Laboratories first as a Postdoctoral Fellow and then as a Member of Technical Staff until 1986 when he became Head of the newly formed Quantum Phenomena and Device Research Department. In 1997, he became Head of Semiconductor Physics Research and was made a Bell Labs Fellow for his scientific contributions. From 2000 to the end of 2002, he was Vice President for Physical Research at Bell Laboratories, Lucent Technologies. Currently, he is the Robert Wallace of Applied Physics and Vinton Hayes Senior Research Fellow in Electrical Engineering at Harvard University, Cambridge, MA. He is internationally known for his research on the quantum design of new artificial materials and devices, known as band-structure engineering, which have opened up new directions in electronics, photonics, mesoscopic physics, and nanotechnology. Among his inventions is the quantum cascade laser, a fundamentally new light source, which has now been commercialized. More recently, he initiated a new line of research using MEMS to investigate the physics of the Casimir effect and its applications to nanomechanics. He has coauthored over 300 papers, has edited four volumes, and holds over 55 U.S. patents.

Dr. Capasso's awards include the King Faisal International Prize for Science, the IEEE Edison Medal, the American Physical Society Award, the Arthur Schawlow Prize in Laser Science, the Wetherill Medal of the Franklin Institute, the Wood Prize of the Optical Society of America (OSA), the William Streifer Award of the IEEE Lasers and Electro-Optics Society, the Rank Prize in Optoelectronics (U.K.), the IEEE David Sarnoff Award in Electronics, the Duddell Medal of the Institute of Physics (U.K.), the Willis Lamb Medal for Laser Science and Quantum Optics, the Materials Research Society Medal, the "Vinci of Excellence" Prize (France), the Welker Memorial Medal (Germany), the New York Academy of Sciences Award, and the Newcomb Cleveland Prize of the American Association for the Advancement of Science. He is a member of the National Academy of Sciences, the National Academy of Engineering, the American Academy of Arts and Sciences, and the European Academy of Science. He is a Fellow of OSA, APS, SPIE, and American Association for the Advancement of Science (AAAS).