THE DECADE IN OPTICS

is a strong invitation for the development of interferometry of soft x-ray wavelengths. Such a capability will be an essential ingredient in the development of diffraction limited multilayer coated imaging optics.

Perhaps the most interesting industrial spin-off from the revolution in x-ray optics may be the development of a new technology for the mass production of high density integrated circuits. Soft X-ray Projection Lithography (SXPL) uses multilayer coated reduction optics to project an image of a reflecting x-ray mask onto a resist coated wafer (see Figure 3). The ultimate resolution of this technique far exceeds that of any other technology proposed for high throughput I.C. production. Recently AT&T demonstrated a resolution of 500Å using a SXPL system with 20:1 reduction optics at 140Å.12

Figure 3. A possible projection x-ray lithography system using a reflecting multilayer x-ray mask and a pair of multilayer coated mirrors for high-resolution imaging optics. As an advanced technology, this system would allow industry to benefit fully from the resolution advantages of operating at shorter wavelengths.

References

The decade of the '80s was the time when many of the dreams of the '70s in laser cooling and trapping of atoms became reality. It was also a time when accidental discovery led to totally new areas of research and deeper understanding of the basic ideas of laser cooling. Indeed, the “technology” of the manipulation of atoms has exceeded the expectations of the first proposals during the 1970’s.*

Early theoretical work
The laser cooling of atoms was proposed in 1975 by Hansch and Schawlow1 and Wineland and Dehmelt.2 The key idea was to use the Doppler shift to create a velocity dependent force on ions or atoms. Atoms moving in a region of counter-propagating laser beams will scatter more photons from the beam opposing the motion if the laser is tuned to the low frequency side of the atomic resonance. Also during the '70s, a number of theorists—notably Minogin, Kasantzev, Letokhov, and Stenholm—developed a deeper understanding of light induced forces.3

In 1978, Ashkin proposed laser traps based on the dipole force that results from the induced dipole moment of an atom in a strong

*The spectacular advances in ion trapping that have also occurred during this time are not addressed here due to limited space.
laser field. The electric field of the laser polarizes the atom in phase with the driving field if the frequency of the light is below the resonant frequency. Since the energy of a dipole is $W = \mathbf{p} \cdot \mathbf{E}$, the atom minimizes its energy by moving into the region of maximum laser intensity.

In 1980, Gordon and Ashkin made a rigorous calculation of the heating expected for atoms in both traveling and standing wave light fields. This paper showed that the high intensities needed for dipole trapping would cause heating that would quickly boil the atoms out of the trap. The heating rate was predicted to be especially high for traps that used standing waves such as the one highlighted in Ashkin's 1978 paper.

Neutral traps and optical molasses
Experiments during the 1970s were limited to small changes in the velocity distribution of atoms in an atomic beam, and it was not until the 1980s that researchers began to tackle the challenge of reducing the large longitudinal velocity ($v_{\text{rms}} \approx 5 \times 10^4 \text{ cm/sec}$) in an atomic beam. In the mid-80s, a flurry of experimental results began to pour out. In 1984, Bill Phillips' group at NIST in Gaithersburg and John Hall's Group at NIST in Boulder reported the cooling and stopping of atoms in an atomic beam at a temperature of 50-100 mK. Several months later, magnetic trapping of neutral atoms was demonstrated by the Gaithersburg group, and a group from AT&T Bell Labs showed the three-dimensional confinement and cooling of atoms in "optical molasses". The name molasses was given to the cooling light propagating along the $+x$, $y$, and $z$ axes because of the highly viscous damping force of the light. In the Bell Labs experiment, the temperature of the atoms was measured by a ballistic time of flight technique to be 240 µK.

Optical molasses gave the Bell Labs group a natural means of both loading the atoms into a dipole force trap and, once trapped, a means of keeping the atoms cold. Armed with optical molasses, the group demonstrated the first optical trapping of atoms with a single focused laser beam imbedded in optical molasses. Concurrent with the trapping of atoms with a dipole trap, the Bell Labs workers also showed that the same dipole trapping force could be used to trap macroscopic particles from ~ 20 nm to 5 μm in diameter. Since the trap could be easily moved by moving a mirror or lens, the trap was dubbed "optical tweezers".

A less intuitive form of cooling—often referred to as "stimulated molasses" or "blue molasses"—was predicted in the mid-seventies by Kasantsev and Minogin and Serrima. These authors showed that cooling by counterpropagating laser beams can occur if the laser is tuned to the high frequency side of the resonance and if the light intensity is much higher (many times the saturation intensity) than the intensity used in red molasses. This form of cooling comes about because of the energy level shifts of the atoms induced by an intense light field create a periodic set of potential hills. In the so-called "dressed-state" picture used to describe the strong atom-field coupling, the energy states of the atom in a strong standing wave are described by an infinite set of "hills and valleys". Each energy manifold differs in energy by one photon quanta of energy. Atoms lose kinetic energy moving up a hill, and at the top of the hill, they have a high probability of spontaneously emitting a photon that would place the atom at the bottom of another manifold of potential hills. The Paris group that demonstrated this type of cooling named it "Sisyphus cooling" after the poor soul forever condemned to roll a boulder up to the top of a never ending set of hills.

Although the limiting temperature of Sisyphus cooling is higher than the standard molasses, the cooling rate can be more than an order of magnitude higher. A significant advance in trapping was made in 1987 with the invention of the magneto-optic trap, a trap comprised of modest magnetic field gradients and, circularly polarized light. The low intensities needed for this trap mean that the trapping volume can be made much larger than that of a dipole trap and a separate cooling frequency is no longer needed. Over $10^8$ atoms were trapped at densities in excess of $10^{11}$ atoms/cm$^3$ by the MIT/Bell Labs collaboration that developed this trap. At these densities, the sample of cold atoms is optically thick. Using this trap as a starting point, studies of ultracold collisions by Prentiss and collaborators, and Wiemann's group at Boulder have been carried out.
Trapping of metastable neon has been also demonstrated. Work is presently under way to use this trap as a starting point in an effort to achieve Bose condensation of a dilute gas. Earlier studies of associative ionization in a strong light field have been done by the NIST group using a two beam dipole trap. A strong light field have been done by the NIST group using a two beam dipole trap.

Cooling below the Doppler limit
A major surprise in the short history of laser cooling was the 1988 discovery by the NIST group in Gaithersburg that optical molasses could cool sodium atoms to temperatures almost an order of magnitude below the minimum temperature predicted by theory based on a two level atom. Within months of this finding, the Paris group and the Stanford group verified the work and proposed a new theory of laser cooling. The new type of cooling requires the interplay of several effects in atoms with magnetic (Zeeman) sub-levels. Different Zeeman levels have different light shifts, and atoms in a light field with a particular polarization "optically pump" (a process that alters the ground state population of the atoms by repeated absorption and emission of light) into a state of lower energy. If the atoms then move non-adiabatically into a region of space with different polarization, the internal energy of the atom increases at the expense of the kinetic energy. The optical pumping process then dissipates the internal energy by returning the atom to a low energy ground state. One prediction is that the minimum temperature should be on the order of $k_B T = m <v_{rms}^2>$ where $v_{rms}$ is on the order of several times the velocity change due to a single photon recoil. For cesium atoms, temperatures as low as 2.5 µK, corresponding to 3.6 photon recoils have been measured.

One dimensional experiments of optical molasses with and without polarization gradients have been compared to one dimensional theories by the Stanford group. As a corollary to polarization gradient cooling, the group also showed both theoretically and experimentally that sub Doppler limit temperatures can be obtained without polarization gradients. This effect was subsequently discussed in greater detail by Metcalf and his collaborators.

Cooling below the single photon recoil "limit" has also been demonstrated by the Paris group. They showed that an atom between a $J = 1$ to $J = 1$ transition with counterpropagating $\sigma^+$ and $\sigma^-$ light has a "non-absorbing" state $\Psi_{na} = \sqrt{2} \{ g, p + \hbar k \} / \sqrt{2}$. For $p = 0$, $\Psi_{na}$ is completely transparent to the light. In this cooling scheme, atoms will scatter photons, randomly walking in momentum space until they scatter into a state with low enough momentum $p$ so that $\Psi_{na}$ will not oscillate (because of the different de-Broglie frequencies of the $p + \hbar k$ and $p - \hbar k$ states) into $\Psi$, during the time the light is irradiating the atom. After a given time in the light field, some fraction of the atoms will have collected near the momentum states with $p = 0$. The group demonstrated transverse cooling of a beam of metastable helium atoms to a temperature of 2 µK, a factor of 2 below the single photon recoil temperature.

Atom optics and non-optics
Atom "optics" advanced during the decade. Diffraction of atoms with gratings of light due to a standing wave of light and matter gratings were demonstrated at MIT. Atom mirrors made with the evanescent field of totally internally reflected beam of light in a prism were shown to work, first in grazing incidence by Balykin and collaborators and then in normal incidence by the Stanford group.

Atom manipulation techniques with no optical analog have also been introduced. An "atom funnel" that can collect atoms over a large energy range, cool and compress them into a well defined stream, and eject them into free flight at optical molasses temperatures has been reported recently by the Stanford group and also by Wallis and Ertmer. In the Stanford work, the peak phase space density (defined as the number of atoms divided by the spread in position and velocity) has been increased by 4 orders of magnitude compared to a thermal atomic beam.

The Stanford group also constructed an atomic fountain of atoms and used it to measure the ground state hyperfine splitting of sodium. Atoms were first collected in a magneto-optic trap and then launched upwards in a ballistic trajectory. As they turned around due to gravity, the long measurement time resulted in 2 Hz wide resonance line with a statistical uncertainty of 10 MHz after 15 minutes of integration time. Several groups are now building a cesium fountain that can be used to create an atomic clock that will surpass the accuracy of present time standards by one to two orders of magnitude. Work is also beginning on a time standard based on optical transitions. The hope is to improve the present time resolution by as much as 5 orders of magnitude.

Magneto-optic cooling can now be done with inex-
pensive diode lasers and atoms in sealed off glass cells. This development allows the development of the portable clocks of great precision. Also, small samples of rare isotopes or radioactive isotopes can be trapped, opening the possibility of a wide range of nuclear physics and weak interaction experiments.

**Trapping of micron-sized particles**

Trapping of micron and sub-micron sized particles introduced by Ashkin and collaborators is being used by the biology community to manipulate bacteria, viruses, colloids, and sperm, and even extend and pin down a single stretched out molecule of DNA. The tweezers can be easily added to a standard optical microscope; the trapping light is introduced through the objective of the microscope, the manipulation of specimens in thin section in between the microscope slide and cover slip. Optical trapping has also been used to study the formation of crystals and quasicrystals of polystyrene spheres in complex standing wave patterns.

This brief review has only covered a small fraction of the work that has been done in the area of laser manipulation of neutral particles during the last decade. The unprecedented control we can now exert over neutral particles has opened up a wealth of new possibilities. In the next decade, we will no doubt see many more unanticipated developments and witness applications of these new tools in diverse areas of physics, chemistry, and biology.

**References**

38. C. Monroe, et al., to be published, 1990.