at or just after low tide. The earthquake frequency nearly doubled at the lowest tides and at the highest cubic and extensional stresses. This result is similar to that at Axial Volcano (*1*).

The above observations on submarine and terrestrial volcanoes show that earthquakes in volcanic regions near the shore and on mid-oceanic ridges display strong correlations with tidal forces. Fault movements that generate earthquakes may be accelerated by tidal stresses with directions suitable for creating shear movements.

The direction of stress at the critical stage of fault failure and the presence of seawater penetrating into opening cracks at shallow crustal depth may explain why diurnal or semidiurnal changes in earthquake activity have been observed only for short periods during seismic events. By themselves the tidal forces are too small to generate earthquakes, but in the critical stage of faulting they can trigger volcanic earthquakes.

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PERSPECTIVES: APPLIED PHYSICS

Testing the Limits for Resists

Elsa Reichmanis and Omkaram Nalamasu

The invention of the point-contact transistor in 1947 heralded the dawn of the microelectronics era (*1*). Since then, advances in materials chemistry, particularly organic and polymer chemistry, have been crucial to microelectronics technology. Quantitative knowledge of the properties of the materials is crucial for understanding their resolution limits and for developing powerful new materials. On page 372 of this issue, Lin *et al.* (*2*) report a new tool for obtaining such knowledge at nanometer resolution.

Microelectronics technology is driven by the need to build devices that squeeze an ever-increasing number of individual circuit elements onto an ever-smaller piece of semiconductor material (*3*). Today, a state-of-the-art, fully processed silicon substrate containing hundreds of complex devices with millions of transistors each is not much larger than the first silicon-based single transistor fabricated in 1947 (see the figure).

The ability to shrink the feature size depends on the lithographic techniques used to make the circuit pattern. In optical lithography, light-sensitive materials (photoresists) are used to transfer the desired pattern to the wafer (*3*). A photomask blocks resist exposure in certain areas; in the exposed areas, the resist becomes soluble to the developer.

The resolution of an optical lithography projection system is limited by

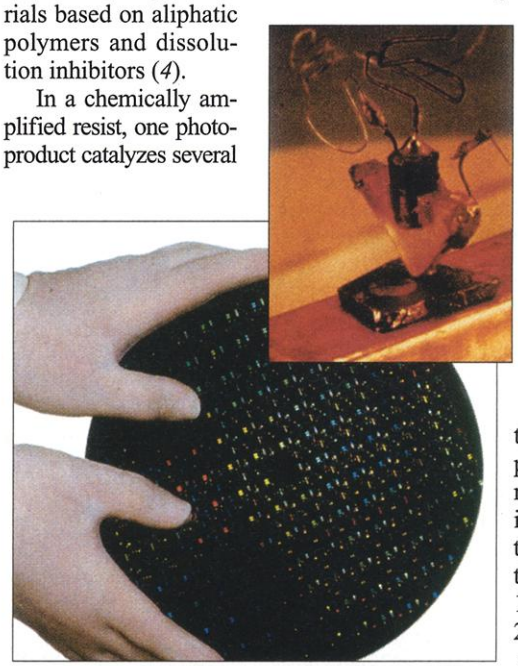
$$w = k\lambda/\mathrm{NA} \qquad (1)$$

where w is the minimum resolvable feature, k is an empirical constant determined by the resist process used, λ is the exposure wavelength, and NA is the numerical aperture of the optical exposure tool.

Increasing NA or decreasing λ improves the overall resolution of the system. But the depth of focus decreases with increased NA, and avoiding spherical aberrations is difficult in very high NA optical systems. It is therefore desirable to use smaller wavelengths to improve resolution at high NA.

Use of smaller wavelengths in turn necessitates new optical (lens, photomask) and imaging (photoresist) materials and processes. When new optical lithographic technologies that use smaller wavelengths—especially 248 and 193 nm—were introduced, chemists responded by developing chemically amplified resist material technologies and 193-nm resist materials based on aliphatic polymers and dissolution inhibitors (*4*).

In a chemically amplified resist, one photoproduct catalyzes several hundred chemical events, thereby accelerating resist transformation. Hence, less ultraviolet light is required to form an image in the resist, and finer features with improved accuracy can be created. The mechanism (*5*) enabled the conflicting requirements of high sensitivity (low dose) and process tolerance to be balanced. It was the first revolutionary change in resist materials chemistry, leading to very sensitive, robust, high-resolution resist systems.



Silicon-based transistor technology today and in 1947 (inset).

The advent of 193-nm photolithography resulted in yet another paradigm shift in resist material design. Traditional UV and deep-UV organic matrix resins were opaque at this wavelength. With 193-nm resists, the challenge was to design a resist system that was largely based on aliphatic components (polymers and dissolution inhibitors) but functionally identical to earlier resists built on poly(hydroxystyrene) and novolac resin chemistries (*6, 7*).

Materials and process modifications using chemically amplified resist technologies have enabled the extension of optical lithography to the sub–100-nm regime. The ultimate resolution capability of a resist is governed by a complex set of molecular interactions involving the matrix resin, photoacid generator, acid strength, acid and counterion molecular size, acid diffusion, environmental contaminants such as airborne bases, etc. The fundamental properties governing the intrinsic resolution limits of chemically amplified resist materials have largely been unexplored.

As noted by Lin *et al.* (*2*), quantitative measurements of material and transport properties in resist films with nanometer resolution are of paramount importance to understanding the resolution limits of candidate materials. When the critical device dimension falls below 100 nm, the required linewidth control of 2 to 5 nm approaches the molecular size of each individual polymer molecule (*8*). This necessitates qualitative—and, perhaps more important, quantitative—

The authors are at Bell Labs, Lucent Technologies, Murray Hill, NJ 07974, USA. E-mail: er@lucent.com, nlms@lucent.com

understanding of the molecular events that take place during resist coating, pre-exposure baking, exposure, post-exposure baking, development, and drying.

Lin *et al.* report an important step toward this goal by demonstrating the use of x-ray and neutron reflectometry as a general-purpose tool to directly measure acid diffusion and the deprotection reaction front in chemically amplified resists with nanometer resolution. This technique allows exploration and identification of the fundamental chemical and transport mechanisms that are operational in candidate resist materials chemistry systems.

The work of Lin *et al.* opens a window of opportunity to construct structure-property relationships between chemical transport mechanisms and ultimate resist resolution. It may also lead to insights into the ultimate, intrinsic resolution limits and critical dimension control of polymer-based imaging materials.

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PERSPECTIVES: SEA LEVEL CHANGES

How Alaska Affects the World

Mark F. Meier and Mark B. Dyurgerov

As global sea levels rise, scientists are struggling to quantify the contributions made by glaciers around the world. On page 382 of this issue, Arendt *et al.* (*1*) report an important piece of the puzzle. They show that the Alaskan glaciers produce more meltwater than previously allowed for in models. Future sea level changes may therefore be underestimated.

The societal and economic impacts of rising sea levels are already evident (*2*). Beach erosion and shoreline retreat impact valuable real estate and the livelihood of many waterfront communities. Sea level changes affect the rate of saltwater incursion into coastal aquifers, the extension of the saltwater wedge in estuaries, and the probability of damage from storm surges along coastlines. More than 100 million people live within 1 meter of the mean sea level, and the problem is especially serious for low-lying small island nations.

Global sea level rise is caused mainly by ocean expansion due to warming (steric rise) and by ocean mass increase due to the melting of glaciers on land (eustatic rise). The laser-altimeter surveys of Alaskan glaciers reported by Arendt *et al.* (*1*) add fuel to a controversy about the relative importance of these contributions (*3*).

Estimates of the global contribution of glaciers (not including the Antarctic and Greenland ice sheets) to sea level rise are traditionally based on labor-intensive mass-balance (snow/ice input minus ice/water output) measurements on the glacier surface (*4*, *5*). Many such measurements have been made on small- to medium-sized glaciers in Europe, but the larger glaciers in other parts of the world are poorly sampled.

Alternatively, numerical models of global glacier wastage may use temperature and precipitation data calibrated by a limited number of mass-balance observations (*6*, *7*). These models suffer from the paucity of precipitation data in some highly glaciered parts of the world. Serious problems exist with both approaches in southern and southeastern Alaska and adjacent Yukon/northwestern British Columbia.

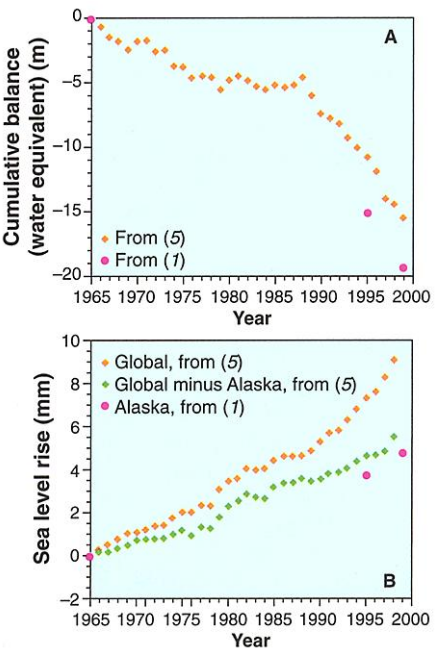
The mountains around the Gulf of Alaska contain up to 90,000 km^2 of glacier area. They include the largest glaciers outside of the polar regions and are characterized by very high rates of precipitation and runoff—as much as 4000 mm/year. However, long-term mass-balance time series are available for only three relatively small glaciers in the region—Gulkana, Wolverine, and Lemon Creek Glaciers—totaling just 53 km^2.

Are these data representative of the many large glaciers? According to the results of Arendt *et al.* (*1*), they are. For the three glaciers mentioned above, laser-altimeter results and mass-balance observations agree within the error limits (*8*) (see panel A in the first figure). The wastage of these glaciers follows a global trend of accelerated melting since 1988 (see the second figure) (*9*).

This consistency allows an assessment of the impact of all Alaskan glaciers on global sea level. The Alaskan glaciers (see panel B in the first figure) (*1*) contribute about one-half that of all glaciers worldwide, although Alaska contains only about 13% of the world's glacier area. This result was suggested earlier on the basis of a rather dubious model (*10*), but recent precipitation/temperature model results (*6*, *7*, *11*) grossly underestimate the Alaskan contribution. Unfortunately, these climatic models are the basis for most published projections of future sea level rise (*3*).

Recent models used for projection allow for the shrinkage of glacier area that accompanies thinning (*3*, *11*). The larger the glacier, the less the relative decrease in area for a given loss of thickness. The huge glaciers of Alaska are now seen to be major contributors to sea level rise; unfortunately, they were not included in published inventory data used in (*3*, *11*). The future rate of decrease in area, and hence in melt volume, will be less than estimated in these recent models. This is another reason why existing projections underestimate future sea level rise.

Recent studies (*12*) indicate that the global pattern of sea level rise measured by satellite altimetry for 1993 to 1998 matches the calculated thermal expansion of ocean waters, leaving little room for a eustatic component. In contrast, Earth rota-



The melting of Alaskan glaciers. (**A**) Surface mass-balance observations (*5*) and laser-altimeter measurements (*1*), averaged for three Alaskan glaciers (*14*). (**B**) Sea level rise due to glacier wastage, including area-weighted global total based on mass balance (*5*), global total minus Alaskan glaciers (*5*), and Alaskan glacier total from laser-altimetry (*1*). The latter two curves are approximately equal, showing that Alaska provides half of the total contribution of glaciers to sea level rise (*14*).

The authors are at the Institute of Arctic and Alpine Research, University of Colorado, Boulder, CO 80309, USA. E-mail: mark.meier@colorado.edu