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Large-area microprocessing with excimer lasers

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Abstract Pulsed excimer lasers are the by far strongest and most efficient laser sources in the ultraviolet spectral region. On account of the unique lateral resolution of 1 µm, which is achievable with excimer-laser based processing systems as well as of the large field size covered within each laser shot, excimer lasers are indispensable laser sources in pulsed-laser deposition, high-precision marking, low-temperature surface annealing and large-area micropatterning.

The innovative potential of excimer lasers and related beam delivery technology for large-area processing applications is reviewed.

1 Introduction

UV wavelengths are advantageous because the high energy photons can remove material by direct bond breaking in most materials, including plastics and glasses. This photoablation process generates virtually no heat and hence only marginal peripheral thermal damage as compared to longer wavelength lasers, particularly in the infrared [1]. In contrast, longer wavelength lasers remove material by intense local heating, which inevitably causes a heat-affected zone (HAZ). In addition, most plastics have a UV absorption spectrum characterized by sharp peaks. The availability of several output wavelengths means that it is often possible to match one of these peaks very closely, leading to highly efficient material removal.

Due to diffraction effects, short wavelengths can also be imaged to a much smaller feature size than longer wavelengths, which enables the production of features at much higher spatial resolution. This has proven to be a critical benefit in many applications requiring very small features down to a few microns.

2 UV laser technology landscape

With industrial processes, throughput rate is as important as process quality. The excimer laser offers excels in this area because it delivers both very high pulse energy and very high average power. Simply stated, the higher the pulse energy, the more material is removed with each pulse or the larger the area covered with each single excimer-laser pulse [2]. The high output power in combination with the unmatched resolving power enables thus the fast production of micron-sized features over large areas as required e.g. for flat-panel display manufacturing. The latest generation of excimer lasers is now available with output powers of over five hundred watts. As shown in Fig. 1, other ultraviolet (UV) laser technologies relying on frequency conversion do not even come close to excimer technology as to the average output power.

3 Large-area UV beam concepts

Treating large areas in minimum times is often an essential prerequisite in industrial processing [3]. While excimer

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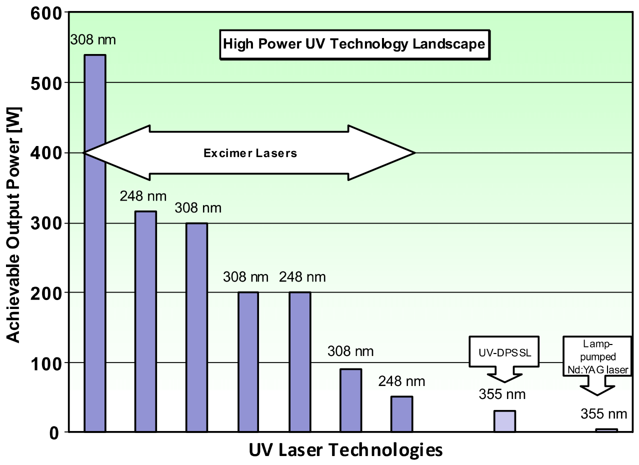

Fig. 1 Comparison of UV power (355 nm and below) available from current high pulse energy laser types

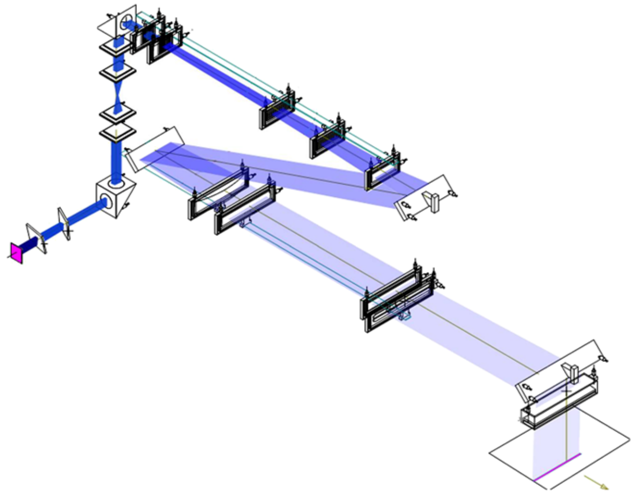

Fig. 2 Layout of an optical train for shaping large line-beams from high-power UV excimer lasers

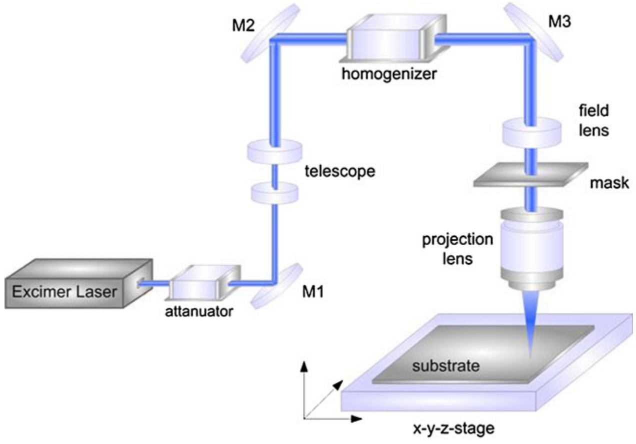

Fig. 3 UV mask projection concept for fast coverage of large-areas with dense and complex repetitive patterns

lasers offer intrinsic advantages for precise large-area treatment, exploiting their full potential in industrial UV processing relies on the appropriate beam delivery architecture. Depending on the application highest throughputs are achieved with enabling beam delivery concepts such as line-beam scanning and step and repeat mask imaging [4]. The most effective large-area excimer-laser beam architectures and respective applications will be described in the following section.

3.1 Line-beam scanning

Line-beam optics convert the rectangular excimer-laser beam profile which has dimensions of ca. 30 mm × 12 mm into a line-shaped beam profile which covers entire flat panels or wafers in a scanning process. Depending on the application requirements the illumination field size can vary from 50 mm to 500 mm in length and from 0.3 mm to 0.6 mm in width. The building blocks of a high-performance line-beam optics set-up are visible in Fig. 2 where a typical beam path used for low-temperature silicon annealing is depicted. The UV excimer-laser beam enters from the middle-left in the picture where it passes an attenuator and is shaped by telescope optics. Using separate elements for long and short axis homogenization leads to the extremely homogeneous and long-term stable line-shape field, which is necessary for most industrial high-speed, high-quality annealing purposes. In order to realize sufficient UV energy densities of the order of 0.5 $\mathrm{J/cm^2}$ at the substrate which is to be annealed, excimer lasers with high pulse energies of several hundred mJ up to 1 J are employed.

3.2 Step and repeat mask projection

High-resolution UV mask illumination of large substrate panels or wafers aiming at producing precise surface micropatterns such as matrices of holes, grooves or complex circuit structures is effectively done with a high-power step and repeat mask imaging concept as schematically shown in Fig. 3.

The basic building blocks of a mask projection UV beam delivery system are of similar order as in the line-beam optics shown before. The main difference is, however, that a mask containing the pattern information is homogeneously illuminated and imaged down to the substrate with a projection lens by a factor of typically 5 to 25. Since the energy density achieved on the substrate increases with the square of the demagnification factor energy densities measured on the substrate range from some hundred $\mathrm{mJ/cm^2}$ to some ten $\mathrm{J/cm^2}$.

On account of the high UV power and short wavelength of today's industrial excimer lasers (see Fig. 1), such mask imaging optical systems are capable of covering large substrate areas of up to 400 $\mathrm{mm^2}$ within a single excimer-laser pulse. Thus providing lateral (horizontal) feature resolutions

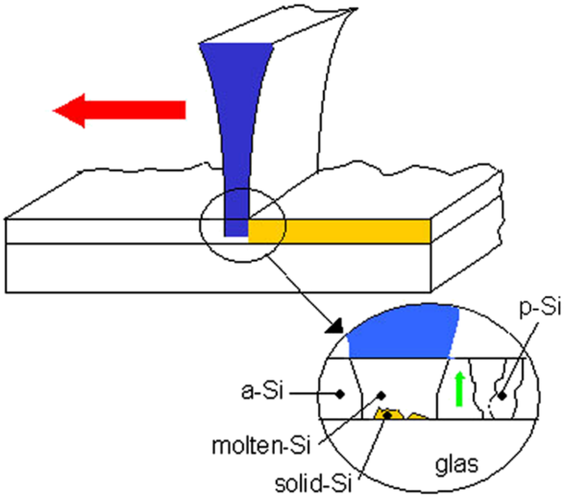

Fig. 4 Schematic view of the excimer-laser silicon annealing process transforming amorphous into polycrystalline silicon

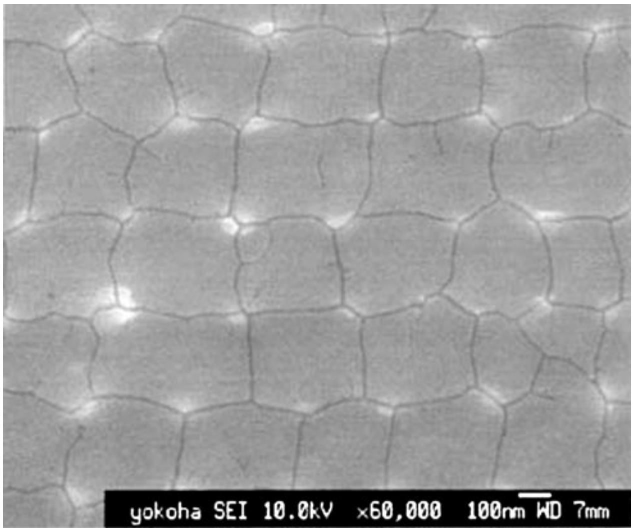

Fig. 5 Microscopic view of grain boundaries in a excimer-laser recrystallized silicon surface

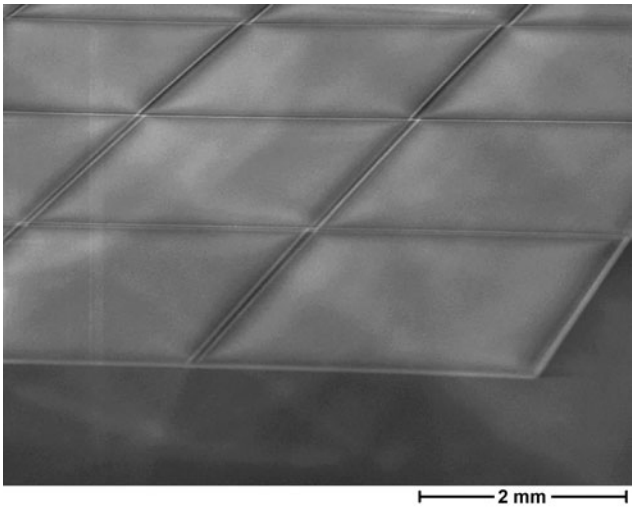

Fig. 6 Microscope image of a one-shot excimer-laser annealed Si (100) wafer surface using a step and repeat process

to the micron level and depth (vertical) resolution to the sub-hundred nanometer level.

Step and repeat mask projection type large-area treatment is used for both surface annealing and surface ablation processing tasks and provide a high degree of pattern reproducibility.

The following section is aimed at illustrating the capabilities of large-area UV microprocessing as to achievable production rate and potential for process upscaling, giving real-world industrial application examples.

4 Large-area UV applications

Precision and productivity are indispensable factors in industrial microprocessing. Sophisticated UV beam delivery systems fueled by the enabling UV output power of today's mature excimer-laser technology meet these requirements as will be demonstrated with the upcoming production floor applications.

4.1 Silicon annealing

In low-temperature excimer-laser annealing of amorphous silicon layers the line-beam profile at a wavelength of 308 nm is directed at a silicon coated substrate which is then scanned relative to the pulsing line-beam. With large line-beam dimensions for high process throughput, a high excimer-laser pulse energy of ca. 1 J is necessary to reach the threshold for near-complete melt of a ca. 50 nm silicon layer depth. Recrystallization direction is upwards initiated by amorphous silicon remainders left at the bottom of the layer as depicted in Fig. 4.

State-of-the-art line-beam optics in combination with high-power excimer lasers deliver line-beam dimensions of 465 mm × 0.4 mm. In the flat-panel display industry, the excimer-laser line-beam architecture enables fast silicon recrystallization speeds of over 30 cm^2/s at an excimer-laser pulse repetition rate of 300 Hz. The result is a homogeneous polycrystalline silicon backplane with about 0.3 μm × 0.3 μm grain size shown in Fig. 5 enabling electron mobilities greater than 100 $\text{cm}^2/\text{V s}$. This value is two orders of magnitude higher compared to employing amorphous silicon and represents the basis for next generation high-performance flat-panel display devices.

Low-temperature melt annealing of silicon wafer surfaces is effectively conducted by means of step and repeat large-field mask projection as visible in Fig. 6 where homogeneous 2.5 mm × 2.5 mm square fields at 308 nm were stepped over a 5 inch silicon wafer surface.

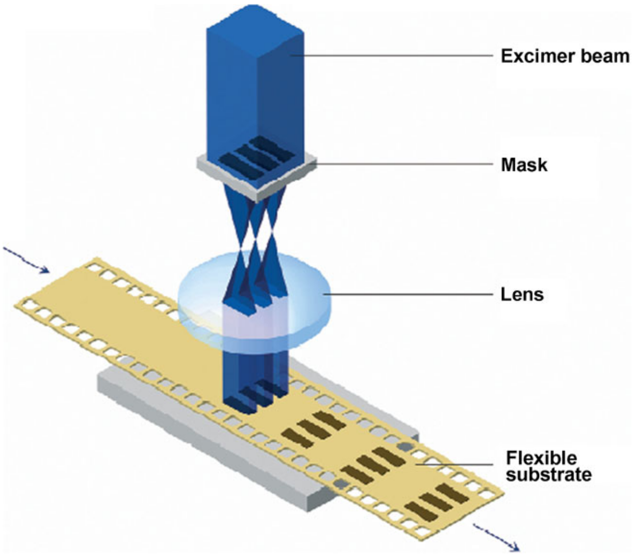

Fig. 7 Layout of an excimer-laser based mask projection system with reel-to-reel sample handling and flexible substrate

Dopant ion activation by low-thermal budget excimer-laser annealing is pivotal for the development of high-performance miniaturized electronic switching devices [5]. Full surface melt annealing activation of boron ions implanted at a dose of 1.6×10^{14} cm^{-2} and with an energy of 15 keV yield wafer surface resistances as low as 110 mV/mA [6]. Due to the single crystalline nature of the wafers melt annealing is done at relatively high energy density of 3 J/cm^2 in a single-pulse process. Large field sizes of several square millimeters and high-power excimer lasers support throughput rates of 200 wafers per hour.

4.2 Reel-to-reel surface engineering

A particularly effective concept is combining mask projection with reel-to-reel processing shown in Fig. 7.

Laser direct patterning enables repetitive production of complex patterns such as sensor circuits on flexible substrates. In this technique, the homogenized excimer-laser beam passes a mask containing the pattern for one or even several complex circuits and is imaged onto a flexible polymer substrate on which a thin 50–150 nm metal layer has been deposited. At 300 Hz repetition rate single-pulse direct patterning can generate 18 000 circuits per minute at substrate feed rates of tens of meters per second [7].

Laser direct patterning can be used with several different flexible plastic substrates (PET, polyimide, PEN, and PMMA) and a full range of conductors including copper, gold, silver, platinum, aluminum, and even titanium. Also for high reel-to-reel feed rates structure sizes of better than 10 μm are easily obtained using excimer-laser wavelengths of 248 or 308 nm as shown in Fig. 8.

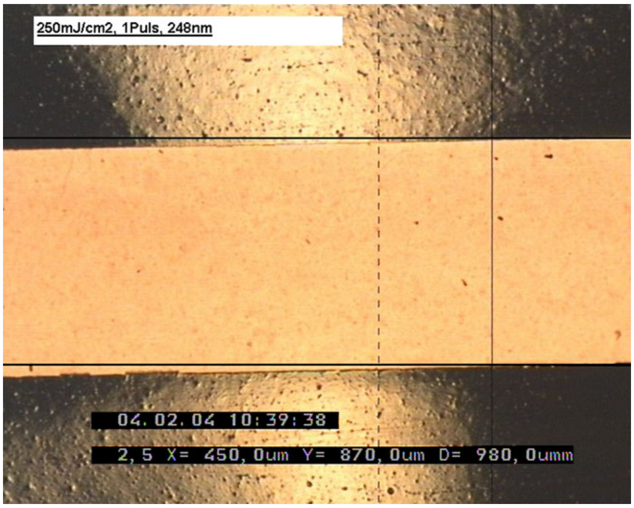

Fig. 8 Single-shot ablation of 30 nm thick aluminum on polyethylene terephthalate (PET) foil at 248 nm and 250 mJ/cm^2

There is growing demand for low unit cost, miniaturized electrical circuits and large-area, reel-to-reel UV processing lends the required precision and productivity for antennae circuits, disposable medical sensors and the like.

5 Conclusions

Increasing product miniaturization has created challenges for manufacturers in many branches. Often, traditional production processes are too slow, unable to achieve the necessary precision, or simply not cost-effective. Miniaturization and use of thin film technology in particular is an ongoing trend seen in industrial manufacturing.

In selectively patterning or annealing thin and functional layers which often exhibit a thickness between 50 nm and 1 μm over large areas the excimer laser with its unparalleled UV power and appropriate beam delivery concepts is a key enabler in industrial large-area microprocessing.

References

1. R. Delmdahl, G. von Oldershausen, J. Mol. Struct. **744–747**, 255 (2005)
2. R. Delmdahl, R. Pätzel, Appl. Phys. A **93**, 611 (2008)
3. A. Usoskin, L. Kirchhoff, J. Knoke, B. Prause, A. Rutt, V. Selskij, D. Farrell, IEEE Trans. Appl. Supercond. **17**, 3235 (2007)
4. A. Masters, T. Geuking, Laser Focus World **41**, 99 (2005)
5. B. Rajendran, R.S. Shenoy, D.J. Witte, N.S. Chokshi, R.L. DeLeon, G.S. Tompa, R.F.W. Pease, IEEE Trans. Electron Devices **54**, 707 (2007)
6. R. Pätzel, B. Turk, J. Brune, S. Govorkov, F. Simon, Phys. Status Solidi (c) **10**, 3215 (2008)
7. R. Delmdahl, Laser User **50**, 8 (2009)