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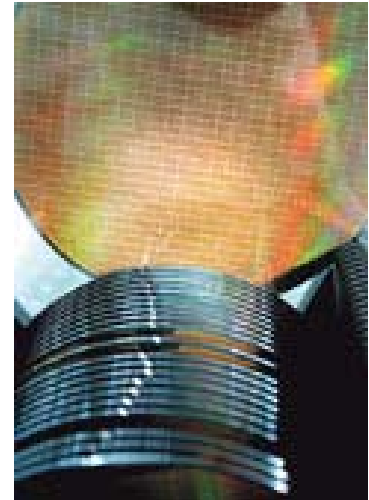
Why qCW is better than CW for the ITRS wafer defect inspection roadmap

Introduction

The ability to detect in-line yield-limiting defects on specific process layers is the primary requirement of wafer defect detection technology. The detection of multiple defect types and simultaneous differentiation at high capture rates, low cost of ownership, and throughput continues to be an important challenge for the semiconductor industry.



The extension of this ability to the diverse throughput requirements of various phases of production — process research and development, yield ramp, and volume production — broadens the applicability of the technology and creates extremely complex solutions that must be fast and sensitive. This is becoming more critical as fabrication facilities begin to run different products in multiple stages of process maturity through the same defect detection tools to extract maximum return from the capital investment in these tools.

Currently, inspection systems are expected to detect defects with sizes scaling down in the same way or even faster as feature sizes defined by technology generations. The need for higher sensitivity of in-line inspections is leading to a dramatic increase in defect counts. It is a challenge to find small but yield relevant defects under a vast amount of nuisance and false defects. At the same time, a low Cost of Ownership (CoO) target for the tools demands high throughput of the inspection. This is in conflict with the issue of improving the signal-to-noise ratio. The keys for successful defect detection are both a high sensitivity and a high capture rate for defects of interest.

Wafer Inspection Physics

The detection of defects and their classification is achieved with wafer inspection technology. Wafer inspection is performed by scanning one or more focused laser spots over the test surface. Wafers are highly reflective, resulting in the capture of both reflected and scattered light. When patterned wafers are illuminated, laser light is scattered by defects, the pattern itself, as well as by rough or grainy surfaces. The amount of laser light scattered, and therefore the sensitivity of the detection, is described by the Rayleigh scattering equation. This relationship defines the relative contribution of incident intensity and wavelength, to sensitivity, for a given optical defect inspection system. Because the sensitivity increases as the fourth power of the incident wavelength, and only linearly with the incident power, virtually all wafer defect inspection equipment suppliers have focused on reducing the incident laser wavelength into the deep ultraviolet (DUV) region as the primary strategy for achieving industry sensitivity and CoO targets.

$$I_s = \frac{\pi^4 r^6}{8 d^2 \lambda^4} \left| \frac{n^2-1}{n^2+2} \right|^2 (1 + \cos^2\theta)\, I_i$$

Is : Scattered light intensity
Ii : Incident light intensity
r : Particle diameter
λ : Wave length
θ : Angle of the incident list
d : Distance from the particle

Laser Technologies

All solid-state lasers achieve wavelengths for wafer defect detection using a technique known as frequency conversion. Frequency conversion is accomplished by passing laser light at a fundamental wavelength, through a non-linear optically active crystal (NLO). Specific crystalline attributes of the NLO material cause the fundamental wavelength to be converted to half of its original wavelength; this process is known as second harmonic generation (SHG). This general technique can be used to produce additional harmonics including the third harmonic (THG), the fourth harmonic (FHG) and the fifth harmonic (SFG). Most solid-state lasers used today in wafer inspection utilize a fundamental wavelength of 1064nm, resulting in a SHG wavelength of 532nm, a THG wavelength of 355nm, a FHG wavelength of 266nm and a SFG wavelength of 213nm.

Solid-state laser designs come in two flavors, continuous wave (CW) and pulsed. CW solid-state lasers emit a constant amplitude laser output. Pulsed solid-state laser designs emit a time varying amplitude laser output. The rate of the amplitude variance in pulsed designs is defined as the pulse frequency. When the pulse frequency is sufficiently high relative to the detection bandwidth of the wafer defect inspection system sensor electronics, the laser effectively appears as a quasi continuous source, or qCW. For the majority of wafer defect inspection systems, qCW laser designs with pulse frequencies greater than 100 MHz deliver comparable results to a CW design.

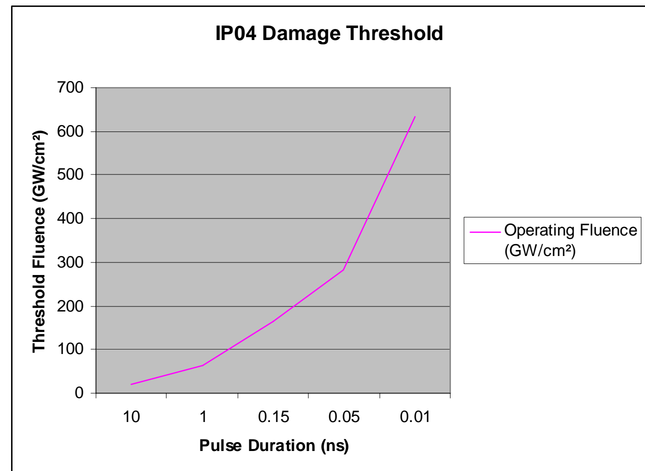
Deep Ultraviolet CW Lasers – CW lasers are defined by the design implementation of a resonating cavity, whose length defines the exact output wavelength of the laser. The resonating cavity length of a CW solid-state laser can be controlled through passive and/or active means. In the simplest design, a passive resonating cavity can employ a single SHG NLO crystal, resulting in direct output of high power, stable 532nm laser light. However, the simplicity of a CW resonant cavity design is lost when it is necessary to achieve lower wavelengths and consequently higher order harmonics. To achieve higher order harmonics at 266nm and below, cascaded resonant cavities, commonly called coupled cavities, are required. Coupled cavities are extremely sensitive to environmental conditions including vibration, thermal variance and acoustic noise. As a result, coupled cavities with integrated NLO crystals become extremely unstable. This is mainly due to the non-linear nature of the frequency conversion process. The efficiency of the process is proportional to the square of the intensity of the incoming laser light. Minor variations in the incoming laser intensity or spectrum, surge through the cascaded cavities at an exponential rate resulting in significant random power fluctuations. It is extremely difficult to successfully control a coupled cavity conversion experiment in a precisely controlled laboratory environment let alone an industrial manufacturing floor.

In addition, extremely stringent demands are required for optical materials which are placed within the CW resonating cavities. Extremely low absorption (<0.2%) in the deep UV and very high damage threshold to CW circulating intensity are but two stringent requirements placed on the NLO and optical components.

For these two primary reasons, solid-state deep UV CW laser designs using conventional NLO materials have been limited to FHG wavelengths with output power less than 1 watt.

Deep Ultraviolet qCW Lasers – Solid-state DUV qCW lasers are characterized by the use of temporally short (~10ps), high intensity (>1kW), high frequency (>100MHz) pulses which pass through multiple stages of frequency conversion in a single pass. The practical limit for the number of frequency conversion stages is dictated by the maximum conversion capability, in the DUV, of the NLO crystal employed. Achieving high power FHG at 266nm and SFG at 213nm strictly becomes a question of the capability of the NLO.

In contrast to CW limitations, qCW designs have virtually no sensitivity to typical environmental conditions. In addition, absorption is a secondary concern; in fact most high intensity systems abandon the use of anti-reflection coatings on the DUV NLO crystals to improve component lifetime. The most striking comparison with CW systems is the advantage of using picosecond pulses. Virtually all NLO's, possess an advantageous attribute in where the damage threshold of the material increases as the inverse square root of the pulse duration. For example, Deep photonic's IP04 has a damage threshold of >20GW/cm² at a pulse duration of 10ns; the damage threshold at 10ps is over 30 times higher, or >600GW/cm². This attribute, coupled with the square intensity law efficiency nature of the frequency conversion process, provides an overwhelming incentive to adopt short pulse, high intensity, high frequency laser designs as the preferred technical direction to achieve high power solid-state DUV laser sources.



Conclusion

The semiconductor industry requires continuing improvement in sensitivity and throughput for both patterned and unpatterned wafer defect inspection. To achieve these goals, wafer defect inspection systems will likely employ solid-state lasers with DUV wavelengths at higher power than they currently utilize. Lower wavelengths in solid-state lasers are accomplished through frequency conversion. Solid-state CW lasers with DUV wavelengths require the implementation of multiple, resonant coupled-cavity designs. Resonant coupled cavities are notoriously unstable, expensive and typically require significant technical maintenance. The prospect of producing and maintaining a triple resonant cavity to achieve the 213nm fifth harmonic of 1064nm, in an industrial environment, is technically daunting and ill advised. In contrast, high peak power picosecond pulses from a fiber-amplified, high frequency mode-locked seed laser can be frequency converted through multiple stages of wavelength conversion with minimal control. This technique provides a direct technical roadmap to wafer defect inspection using 213nm solid-state lasers with low technical risk.

Acknowledgements

References