PROGRESS REPORT ON SHORT-WAVELENGTH SOURCES
AND APPLICATIONS

During 2008-2009 the work at the ENEA FISACC Excimer Laser Laboratory was mainly focused on the development and application of a Micro-Exposure-Tool (MET) for micro- and nano-lithography. The MET is a complex apparatus comprising a laser-driven plasma source called EGERIA, a debris mitigation system, an optical collector and an accurate optical projection system able to print a pattern with a spatial resolution better than 100 nm. The MET-GERIA was awarded of the prize Excellence ENEA 2008 for the industrial application of research tools, and has been proposed as a MIUR Research Infrastructure. Presently, the MET-GERIA is used as an international facility for biologists (in vivo bacteria X-ray microscopy, DNA repair, micro-radiography) physicists (heavy ions generation, X-ray atomic spectroscopy, micro-devices for photonics, contact- and projection-lithography, imaging of sub-micrometric structures on optically active materials) industry (anti-counterfeiting tags).

It is worth mentioning two other experimental activities, respectively concerning the surface coloration of linen textiles for reproducing archaeological images, and the proof of a novel anti-counterfeiting system based on an invisible writing method which uses lithographic techniques on luminescent materials. The experimental results have shown that this technology is suitable to fabricate robust anti-counterfeiting tags, which are almost impossible to counterfeit and can be applied to almost every kind of objects, independent of their shape and size. This technology is patent-pending.

The EGERIA multipurpose source

Since the realization of the first microprocessor in electronic devices, the size of the lithographic patterns has continuously shrunk, allowing an increasing number of transistors per unit area and a dramatic improvement of the flash memory capability. Nowadays, the standard technique for optical lithography is based on ultraviolet lasers and complex projection optics. The best spatial resolution recently achieved is 40 nm. However, the optical lithography has intrinsic limits that cannot be overcome and a shorter wavelength must be used in order to upgrade the spatial resolution to less than 32 nm. The most promising technology to reach this resolution is based on extreme ultraviolet (EUV) radiation, with a wavelength around 14 nm. However, the devices and the materials necessary for this next-generation lithography are very complex and expensive, so that a national project FIRB-EUVL started in 2003 to gather proper Italian skills and to realize a low-cost MET, including the EUV source. This project involved eight Italian partners, namely L’Aquilia University, Padua University, INFN Laboratories of Legnaro, ENEA Casaccia, Media Lario Technologies srl, CNR IFN of Rome, El.En. SpA and our Laboratory, which was responsible for the design, assembling and experimental optimization of the whole MET.

Concerning the EUV source, we used the Laser Produced Plasma facility called EGERIA (Extreme ultraviolet light Generation for Experimental Research and Industrial Applications) developed in our Laboratory (see www.met-egeria.info). The EGERIA facility is based on the use of a XeCl excimer Laser whose beam is focused on a metal tape placed in a vacuum chamber. The features of the emitted radiation (i.e. spectral range, peak intensity, pulse duration) can be managed by adjusting the Laser beam intensity on target and by selecting the target material. The EUV radiation, once cleaned from plasma-debris by an innovative system (protected by two ENEA patents) is managed by a specially designed optical system allowing the radiation to be focused on the reflective mask, where the lithographic pattern is drawn. Finally, the light carrying the pattern information is imaged on the wafer by a Schwarzschild objective projection system with a reduction factor that allows the wished spatial resolution. Figure 1 shows a top view of the EGERIA source
chamber and of the MET chamber. Both vacuum chambers are placed in a clean room, as shown in figure 2.

**Figure 1** Top picture of the EGERIA vacuum chamber (right) where the laser-plasma is generated and of the Micro Exposure Tool high-vacuum chamber (left) where high resolution pattern are written either on a photoresist or on a fluorescent material.

Due to the peculiar features of the laser Hercules, this MET is potentially able to create a lithographic pattern with a single shot, a unique characteristic among worldwide available METs.

In the EUV spectral region (20eV - 200eV) EGERIA emits one of the largest energy per pulse (1 Joule) and longer time-duration (100 ns) among European laser-plasma sources. Thanks to these characteristics, EGERIA is a serious candidate to be used in alternative to synchrotrons and short-wavelength free-electron lasers (FEL) in many applications when the peak power and the brightness are more important than average power. In fact, synchrotron beam-lines are often over-subscribed by factors of three or more; despite the widely-acknowledged advantages of synchrotron radiation, there is not enough to go round. Due to the cost of such sources (more than 100M€ to build, about 1M€ per beam-line per year to run) this is likely to remain the case. The same considerations apply for the short-wavelength FEL that are being developed in different countries, as their size and costs are similar to synchrotrons. In this strategic frame, EGERIA is an alternative, table-top, cheaper, and more accessible source which can offer at least some of the synchrotrons performance.
The laser-plasma facility EGERIA has been successfully used in several interdisciplinary applications, such as LiF irradiation (the LiF target becomes luminescent after EUV exposure), the generation of highly charged ions for injection in particles accumulators, in vivo X-ray microscopy and micro-radiography of biological samples, measurements of high resolution atomic spectra, radiobiology and DNA-repair experiments.

**Linen textile coloration by nanosecond Laser pulses**

After the permanent coloration of linen textiles irradiated by XeCl excimer lasers (emission wavelength $\lambda = 308$ nm) previously demonstrated by our Laboratory, we used an ArF excimer Laser (in collaboration with FISLAS) emitting a shorter $\lambda = 193$ nm wavelength radiation to achieve a very superficial coloration of only the outermost fibers of each linen yarn. The main interest of this work is the search of a mechanism possibly leading to the formation of the Turin Shroud image: in fact, to date no one, not even with state-of-the-art technology has ever duplicated the Shroud image in all its chemical and physical characteristics, and the very thin (about 200 nm) coloration depth is one of the features of the Shroud image most difficult to replicate.

The main difference between the results of irradiations made at 308 nm and at 193 nm is shown in figure 3: we found that the shorter the wavelength, the thinner the color penetration depth, and the narrower the range of suitable Laser parameters. As a consequence, a very precise and spatially homogenous Laser intensity shape is needed to achieve a superficial coloration across large areas. Most important, we have locally achieved a coloration of the 200-nm-thick primary cell wall of the single linen fiber. Finally, we obtained the first direct evidence of latent coloration impressed on linen that appears in a relatively long period (one year) after a Laser irradiation that, at first, did not generate an evident coloration.

In collaboration with FISOTT we also measured the absolute reflectance of our linen samples, and the results match those of the analogous measurements made on the Shroud.

In summary, our results demonstrate that a short and intense burst of 193-nm radiation provides a linen coloration having many peculiar features of the Turin Shroud image, including the hue of color, the color penetration depth and the lack of fluorescence. The comparison of our Laser irradiation results with the characteristics of the Shroud image leads to the conclusion that a short and intense burst of deep ultraviolet radiation may have played a role in the formation of the Turin Shroud image.

![Figure 3](image)

**Figure 3** Cross section of two yarns of linen colored after irradiation at a) $\lambda = 193$ nm and b) $\lambda = 308$ nm. After irradiation at 193 nm, a) shows color penetrates only the outermost fibers in the upper part of the yarn. Both yarns have an average diameter of 300 $\mu$m.

**Novel anti-counterfeiting tags**

Anti-counterfeiting technologies are continuously evolving due to the endless challenge between manufacturers and fake makers. Main goals of anti-counterfeiting systems include traceability and
identification of documents and objects, currency, identity/credit/debit cards, commercial/artistic objects, forensic documents, dangerous wastes, pharmaceutical products, copyright protection systems, quality control.

Unfortunately, none of the available anti-counterfeiting techniques (fluorescent and thermo-chromatic inks/dyes, demetallization, radio-frequency, surface engraving, micro-texts and holograms) used so far offer 100% protection from unauthorized copying or replication. As a consequence, up till now there is no absolute certitude that the documents/objects/cards, spare parts, pharmaceuticals protected by anti-counterfeiting techniques are genuine.

Thanks to the experience on materials irradiation by X-rays emitted by the Laser-plasma source EGERIA, our Laboratory has exploited the capability to write an invisible image on a fluorescent film that can be used as a tag for identification and traceability. This is a novel anti-counterfeiting system that prevents cloning and allows a security degree tailored on the customer’s demand, up to a marking that is impossible to counterfeit. The reading technique comprises a small device that catches the invisible image and, if required, provides a digital decoding of the same image, as shown in figure 4. The reading device has the capability to communicate with local or remote computer systems, and, if required, it can be based on a simple mobile phone digital camera.

We have protected this technology filing both an Italian and an International patent.

At the moment, we are in contact with different Companies interested in integrating our technology into existing anticounterfeiting systems, in order to drastically improve the protection from unauthorized copying or replication of different items.

**Figure 4** Prototype of the hand-holdable device reading the invisible marks. On the PC screen are visible both the raw data matrix (an array of tiny squares as a 2-D barcodes) written on the film as read by the device, and the corresponding pattern “water marking” decoded by a dedicated software.
References (2008 - 2009)

**Patents**


**Published papers**


**Technical Report ENEA**