Continuous-Wave Line Laser For Large Area Material Refinement

High performance technology made in Germany

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In a constantly evolving laser industry new and innovative applications of laser radiation are emerging – in scope as well as in numbers. While pulsed line-shaped laser beams are already well established as mainstream manufacturing tools in the production of flat panel displays, continuous-wave line beam processes are still in their infancy. Nevertheless, they have shown great potential in research & development laboratories as well as in pilot plants for various thermal material processing applications. At Helmholtz-Zentrum Berlin für Materialien und Energie GmbH (HZB) the Helmholtz Innovation Lab HySPRINT operates an open-access laser laboratory where we jointly investigate new and innovative ideas of our cooperation partners and comprehensively evaluate them using a variety of analytical measurement methods on site. Our partners benefit from our profound knowledge on material refinement and analysis. We focus in particular on large area continuous-wave line laser processing of materials. This type of laser sources and the associated manufacturing processes feature essentially unlimited scalability in terms of area and throughput at low costs. So far, we concentrated our efforts on the crystallization of silicon films on foreign substrates offering such films with processes that are compatible to industrial mass production for applications requiring large area, high quality and low cost materials. However, we are open to explore a large variety of different materials.

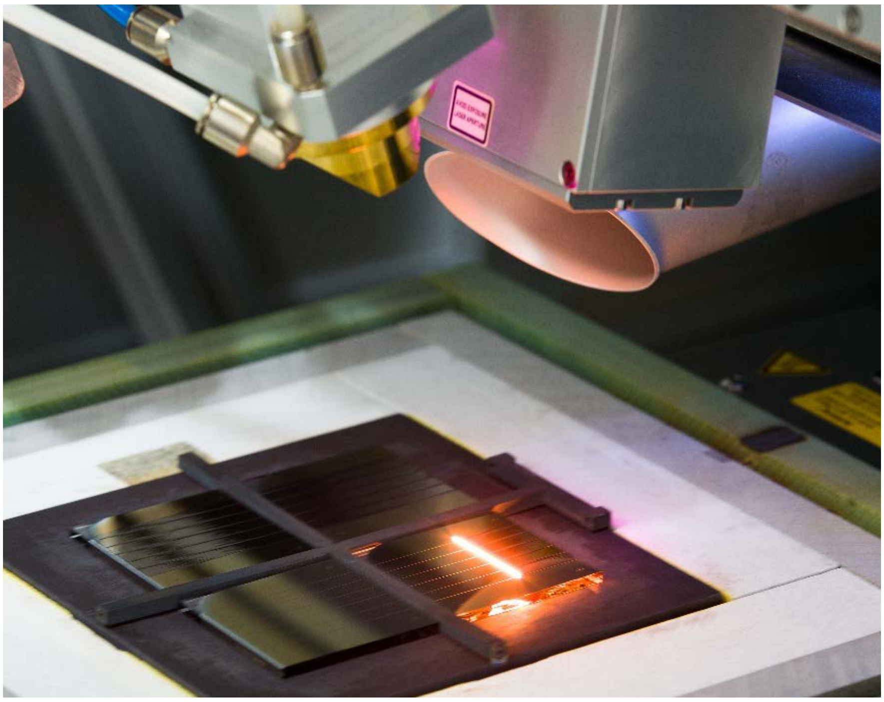

Fig. 1: Line-shaped continuous-wave laser crystallization of a 10 µm thin silicon film on a 3 mm thick glass substrate (source: HZB/HySPRINT)

Line-shaped laser beams

At the HySPRINT laser laboratory of HZB we operate continuous wave line lasers. One example is shown in Fig. 1., technical details are given in the laser laboratory description at www.hysprint.de. In stark contrast to conventional spot-shaped lasers line-shaped laser beams create completely different regimens of material processing. Sweeping a uniform line focus across any surface imprints a well defined planar unidirectional heat gradient into the material stack. The specific properties of line-shaped laser heat treatment have been recognized in many industries and thus found their way into a number of mainstream mass production processes. As one of the more notable examples today more than 80% of all flat panel display devices are mass produced using line-shaped laser beams.

When line laser is the better furnace

The unique features of line-shaped laser heat treatment compared to precision furnaces are related to the much finer spatial and temporal control of energy deposition. This allows for a significantly higher levels of process control and involves:

- spatial adjustment of intensity,
- temporal control of intensity,
- fast and adjustable heat-up and cool-down times.

Particular care is taken in the design of the line beam shaping optics to achieve:

- high uniformity,
- specific profiles,
- large depth of focus.

Efficient material refinement starts with the right choice of the laser source in terms of, e.g., optimal absorption, individual temperature range and optical profiles. Line lasers add precise temporal and spatial control to improve the reproducibility of thermal processes compared to funrnaces. By the combination of the above optical beam shaping design targets and the enhanced process control capabilities line lasers open up new and enhanced capabilities unattainable with furnaces:

- more effective deposition of energy by taking into account the unique properties of the material being irradiated already in the optical design,
- maximized process window and a high process stability due to the spa-

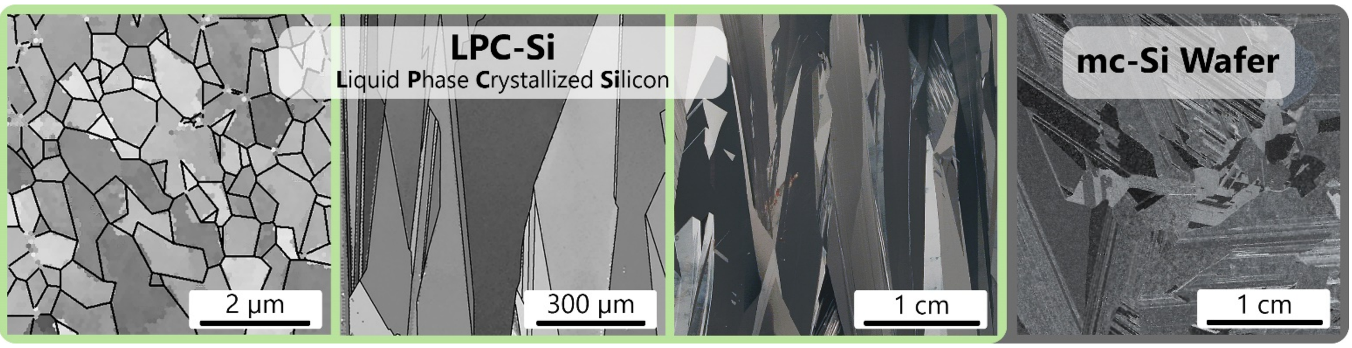

Fig. 3: (left) The green box depicts the flexible grain size tuning achieved with the LPC technology utilizing a line-shaped diode laser. Depending on the crystallization parameters the grain size ranges across several orders of magnitude and can be tuned to fit the desired requirements. (right) A micrograph of a multi-crystalline Si (mc-Si) wafer is depicted in the grey box for comparision (Source: HZB/HySPRINT)

tially and temporally uniform intensity control and its reproducibility

With line-shaped laser treatment as a production tool even extremely sensitive phase transition processes turn out to be not only well controllable, but can be made well-behaved delivering predictable results as well as a high and stable production yields, while maintenance time and costs are low.

The bosonic general nature of light permits photons to pile up on top of each other in space. Extremely large numbers of beamlets can be combined into one seamless laser beam - only limited by the apertures, the beam parameter product, form factors, and related tolerances of the components of the optical beamline. Consequently, not only very high intensities are reached, but also a straight forward unlimited concatenation of separate line focus segments in the lateral direction (long axis of the line focus) are possible.

Continuous wave line lasers for large area material refinement

Most of the superior characteristics of line-shaped laser heat treatment are available even for the simplest possible kind of laser system: the continuous-wave (cw) diode laser. This holds true especially for the virtually unlimited scalability by superposition of beamlets in space and the concatenation of line beam segments in the lateral dimension.

Fig. 2: Continuous wave line laser applications. (Source: HZB/HySPRINT)

An increasing number of laser manufacturers now offer beam-shaped direct diode laser systems up to the multi-kilowatt range of output power. HySPRINT works with high-power, multi-bar (space multiplex) and multi-wavelength (wavelength multiplex) direct diode laser systems.

Based on the available line lasers at the HySPRINT laser laboratory of HZB all kinds of thermal material treatment can be supplied (Fig. 2).

The HySPRINT laser laboratory at HZB currently continues and expands the investigation of laser refinement of photovoltaic relevant materials that had been started in the past by the Institute for Silicon Photovoltaics at HZB. The main focus is on the crystallization and annealing of thin silicon films on foreign substrates. What started as a simple idea has evolved into a mature process and was the advent of the liquid phase crystallization (LPC) technology.

LPC technology: high quality made simple

LPC is a large area crystalline silicon thin film technology. As an advanced zone melting process, it utilizes state of the art line-shaped laser systems to fabricate high quality 5 – 20 µm thick poly-crystalline silicon layers directly on top of foreign substrates. For this purpose, multi-layer systems must first be deposited by means of plasma enhanced chemical vapor deposition (PECVD) and electron beam physical vapor deposition (EB-PVD). Prior to the crystallization process the samples are pre-heated to reduce thermally induced stress. Subsequently a continuous wave line laser is scanned across the coated substrates only once and with adjustable speed up to several centimeters per second.

HZB

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HZB is a research centre for energy materials research, thus contributing to knowledge-based solutions, and it provides large-scale research infrastructure for the national as well as international scientific community and industry. HZB employs about 1200 people and has got an annual budget of about 146 million Euros. HZB is a member of the Helmholtz Association - Germany's largest scientific organisation. In order to stimulate technology transfer the Helmholtz Association has recently established seven Innovation Labs. HZB runs one of them – namely the Helmholtz Innovation Lab HySPRINT (see the other grey box).

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The specifications of the line shaped laser beam are tailored to silicon thin film laser crystallization. As a result, high quality material is consistently achieved over large areas. Its characteristics include:

- high purity
- large crystal grains
- high carrier lifetimes
- high carrier mobilities
- excellent open circuit voltages

Due to our sophisticated laser systems and the excellent beam shaping optics we can benefit of the aforementioned advantages of lasers in general and push the limits of what is currently possible. With smallest changes of the parameter sets and recipes even the crystalline structure of a silicon film and its resulting electrical properties can be tuned to fit the requirements of the material's intended field of end use. As an example, we are able to directly change the resulting grain size depending on the crystallization parameters applied to our layers (see Fig. 3). This allows us to fabricate silicon layers that resemble the small grain structure resulti ng from treatment with pulsed lasers, but also large crystal grains known from multicrystalline Si wafers.

By demonstrating areal high-quality polycrystalline silicon using LPC technology HySPRINT established a new method to manufacture areal sheets of poly-crystalline silicon on glass and other foreign substrates.

HZB has created a material that lends itself for mass production in sheet sizes of a large number of square meters. Demonstrated properties of the material are:

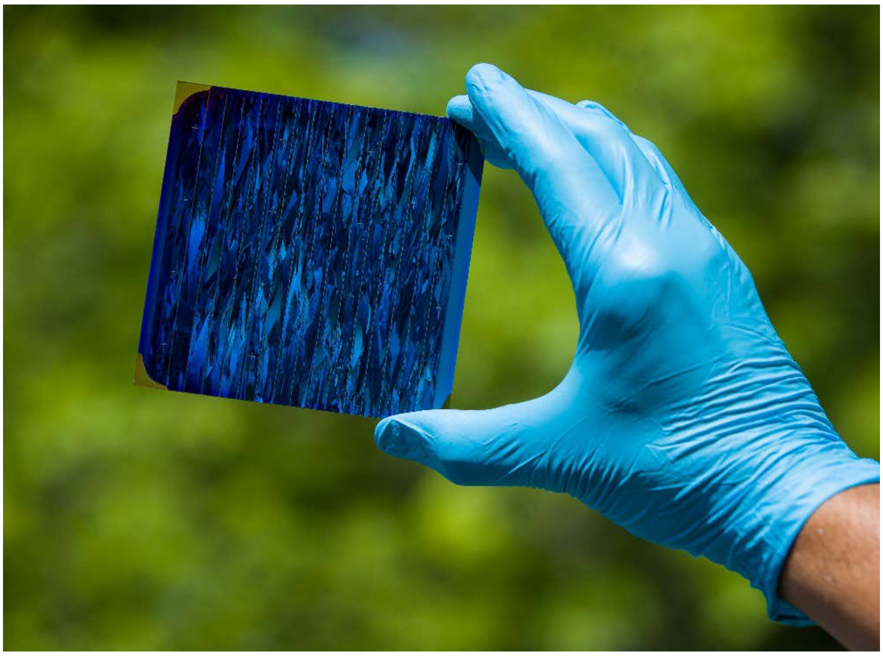

Fig. 4: Si crystal grain structure created by cw line shaped diode laser LPC treatment of a 10 µm Si thin film on 10 cm x 10 cm glass substrate. (Source: HZB/HySPRINT)

- Si thicknesses of a few hundred nanometers up to several tens of micrometers
- Si crystal grain sizes between a few hundred nanometers and several centimeters (Figs. 3, 4)
- carrier mobilities very close to those of mono-crystalline silicon wafers
- processes that are compatible to industrial mass production.

LPC silicon sheets are attractive for end-use applications requiring high-quality low cost areal semiconductor material as can be found in a variety of micro-electronics, MEMS, sensor, or other products.

HZB is currently working with several external partners on validating LPC silicon sheets for industrial use with the goal of prototyping and making available this material for commercial products in

- micro-batteries,
- pressure and humidity sensors,
- OLEDs.

From the lab to the fab

An important part of The Helmholtz Association's core strategy is technology transfer that it promotes by several series of events and programs, including the HySPRINT Innovation Lab (see HySPRINT info box). With HySPRINT HZB continues to further open up basic research laboratories for cooperations with external partners and is actively looking to expand such partnerships.

To this end, for example, LPC silicon sheet technology developed within HySPRINT is validated together with external partners. By targeting to demonstrate the feasibility of laser crystallized LPC silicon as raw material for use in different end-use applications as diverse as micro-batteries, pressure sensors, and OLEDs HySPRINT attempts to bridge the gap between high end mono-crystalline wafers and low cost amorphous silicon thin films or even lowest cost printed electronics. Laser crystallized LPC-Si exhibits a material quality near

Helmholtz Innovation Lab HySPRINT @ HZB

Hybrid silicon perovskite research, integration and novel technologies

HySPRINT provides state-of-the-art application-oriented research and development (R&D) to achieve technological goals and related project milestones for industrial partners.

HySPRINT offers
- an excellent R&D laboratory infrastructure for material and device preparation
- access to all relevant characterization techniques
- a highly competent and motivated team of scientists and technicians
- long-standing experience in close cooperation with industrial partners
- a world-wide R&D network

HySPRINT provides several dedicated laboratories for perovskite, silicon, laser treatment, and nanoimprint lithography research and development.

HySPRINT is operated by the Institute for Silicon Photovoltaics at HZB.

www.hysprint.de

the high end mono-crystalline wafers, but on much larger areas.

Summary

LPC technology provides a straight forward scalable method to produce high quality silicon films in large quantities on square meter sized substrates using in-line manufacturing facilities. LPC offers the potential to significantly reduce costs per square meter compared to standard semiconductor industry grade silicon wafers. LPC-Si sheets could make high end performance available to flexible and areal electronics end-use applications as diverse as, e.g., automotive, wearable electronics, industrial process engineering and illumination technology.

HZB's Helmholtz Innovation Lab HySPRINT supports technology transfer of LPC and other technologies to industry by providing client-specific research and development support as well as cooperation and licensing agreements.

Outlook

The megatrend digitization – often referred to under the headlines Internet of Things (IoT) or Industry 4.0 – entails the growing spread of electronics into all areas of everyday life. More and more everyday objects and personal effects incorporate high performance electronic circuitry of some kind. As a consequence high performance electronics is to be seamlessly installed and integrated in hard to reach nooks and crannies, while minimizing form factors.

Laser crystallized LPC-Si as a large area and potentially low cost high performance semiconductor material platform could be well-suited for flexible, planar electronic indoor and outdoor applications. It could support the megatrend of digitization by making available a new raw material that successfully bridges the gap between high end silicon wafers on the one hand side and low cost amorphous silicon thin films as well as printed electronics on the other hand side.

Authors

Dr. Sven Kühnapfel is one of the leading scientist in the field of LPC technology at Helmholtz-Zentrum Berlin, responsible for start-up creation. As an expert in the field of semiconductor science and material refinement with energetic radiation he lectures at 'Technische Universität Berlin' and Unitversity of Applied Sciences (HTW) in Berlin.

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Dr. Stefan Gall is a senior scientist at HZB where he is currently in charge of the Helmholtz Innovation Lab HySPRINT. He has conducted R&D on thin crystalline silicon films for photovoltaic applications for many years – not only at HZB but also as Technology Director at the company CSG Solar. He has authored/co-authored more than 100 papers. Since 2002 he also teaches at 'Technische Universität Berlin'.

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