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NUOVA OFFICINA ASSERGI: a novel infrastructure for the production of cryogenic and radiopure Si-based photodetectors

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The NUOVA OFFICINA ASSERGI (NOA) is a new facility for the production and integration of large-area silicon photodetectors operating at cryogenic temperatures. Silicon photomultipliers are proving to be a promising technology for next-generation experiments searching for rare events in underground laboratories. New photosensor technology with high performance at cryogenic temperature has been developed by Fondazione Bruno Kessler (FBK) and integrated at Laboratori Nazionali del Gran Sasso (LNGS) into large-area optical units, thus opening the frontiers toward the realization of scalable liquid argon experiments probing dark matter. The massive production of such detectors is now feasible in NOA, a clean room of 421 m^2 designed to operate in a radon-free mode. NOA, commissioned and operational at LNGS, hosts the most advanced packaging machines and electronic test facilities for the integration of silicon devices in a dust-controlled environment. The infrastructure layout is split into two experimental areas: one for the production of electronic devices and cryogenic temperature tests and the other for operating with large detector installations. The NOA facility can be operated with a radon abatement system, making it a unique facility for packaging and testing SiPM-based photosensors and for assembling detector components in a radon-free environment. Therefore, NOA supports the deployment of underground experiments at LNGS and the development of new technologies for the search of rare events, such as dark matter and neutrinoless double-beta decay.

KEYWORDS

clean room, silicon photomultipliers, packaging, photodetectors, cryogenics, radiopurity

1 Introduction

In the last few decades, silicon photomultiplier (SiPM) detectors [1] have obtained overwhelming success and worldwide recognition in the detection of low photon fluxes due to their key features, such as low operating voltages, insensitivity to magnetic fields, robustness and reliability, high performance at cryogenic temperatures, and scalability in creating large arrays. Such characteristics make them attractive for a variety of scientific applications, such as large-scale time projection chambers (TPCs) based on noble liquids searching for rare events in extremely low background conditions. The collection of scintillation light is crucial to detecting neutrino or dark matter interactions in cryogenic environments. One of the issues

FIGURE 1
Left: NOA CR3 test area. Right: NOA CR2.

with large cryogenic detectors for low background applications is the amount of radioactive contaminants in electronic components, connections, and cabling. Typically, SiPMs cover active areas of several tens of square millimeters. This means that for a large surface experiment, a huge number of devices and readout channels are in the close proximity to the detector electronics. To overcome this issue, one possibility is to group SiPMs into arrays to achieve a larger surface that could be read as a single-channel device. Since 2014, FBK (https://www.fbk.eu/it/), in synergy with LNGS, has been working on the development of SiPM arrays [2] of cryogenic photosensors [3, 4] with large aggregated output [5] and has operated successfully with high performance at cryogenic temperatures. This represents a big technological challenge, as in the case of the DarkSide-20k dark matter experiment [6], which aims to build thousands of SiPM-based optical units for an overall sensitive surface exceeding 20 m^2. The massive production of SiPMs has been successfully transferred to LFOUNDRY (www.lfoundry.com), while the photosensor packaging and integration will be operated inside the NOA clean room [7]. In this paper, we will review the main features of the NOA facility, the description of the packaging machines and tools, the technological solutions available, and future perspectives.

2 NOA infrastructure

Born within the framework of the DarkSide-20k experiment, the NOA infrastructure is an ISO-6 clean room according to the ISO 14644-1 standard classification[1], with an overall surface of 421 m^2. It is divided into two main areas: the first, named CR3 (Figure 1, left), is devoted to the packaging, testing, and assembly of cryogenic large-area SiPM-based devices; the second, named CR2 (Figure 1, right), is designed for handling and mounting of big detectors. The infrastructure also includes two dedicated small rooms, namely, the dressing room (CR1-IS) and the pass-box (CR2-IS), while a third area (HVAC), approximately 42 m^2, is completely dedicated to the air ventilation system. All the environments are sketched, as shown in Figure 2.

NOA CR3, with a surface area of 353 m^2 and a height of approximately 3 m, hosts 25 workbenches, is provided with different utilities (gas nitrogen, vacuum, compressed air, electricity, LAN, and telephone line), and is equipped with antistatic mats in order to prevent electronic component damage due to electrostatic discharges. A liquid nitrogen charging station has also been set up for the filling of small dewars for device characterization at cryogenic temperatures. Two chemical hoods have been installed, each equipped with compressed air, gas nitrogen, and vacuum; one of them is also provided with a deionized water sink. Furthermore, two water sinks equipped with both industrial and deionized water are available inside the CR3 and a 5 °C chilled water line. All the distribution pipes of the mentioned utilities, together with the electrical lines, are located above the counter ceiling of the clean room in the space dedicated to the air plenum. Utility columns are placed in correspondence with the workbenches and the production machines to provide rapid connections. CR2 covers a surface area of 68 m^2 with the purpose of integrating large experimental setups[2]; for this reason, the room height is 5.8 m and the floor has been designed to withstand a

1 Referred to the maximum particle concentration suspended in one m^3 of air, an ISO 6 clean room allows a maximum of 1×10^6 (one million) particles of 0.1 micron size.

2 The DarkSide-20k TPC optical planes will be assembled in CR2 before installation in the apparatus in the LNGS underground cavern.

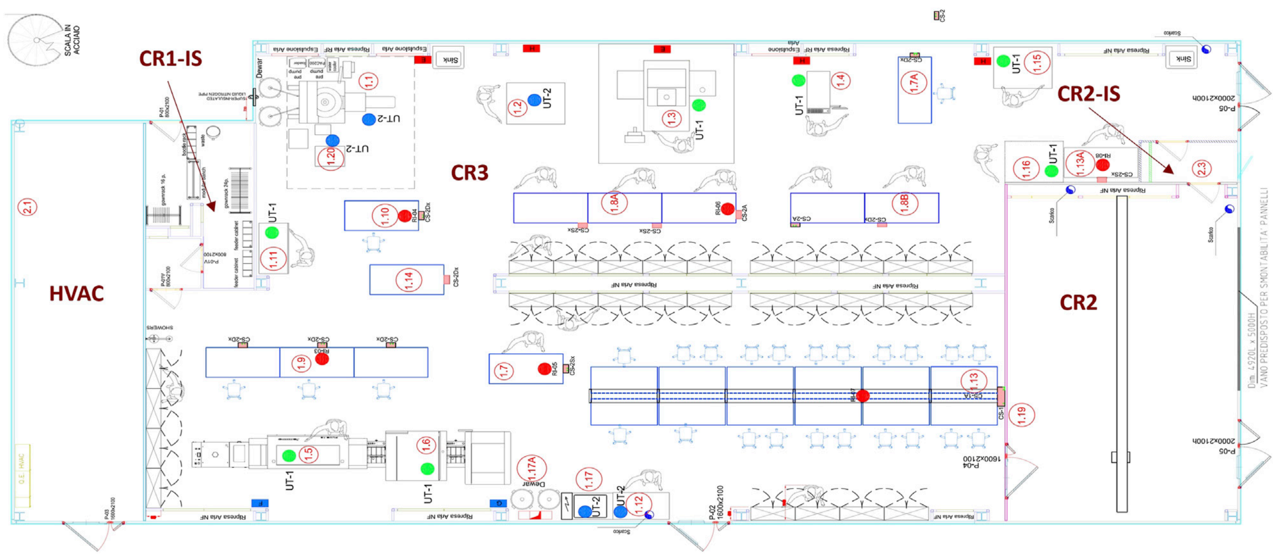

FIGURE 2
NOA clean room layout.

nominal load of 2000 kg/m^2 although it has been successfully tested with a 3,000 kg/mm^2 load. In CR2, a 2-ton manual crane is also available. A dedicated air lock allows entry to CR2, while CR3 is off. The air lock can be also used as a "pass-box" for the transfer of materials inside/outside the clean room since it is provided with a dedicated window properly interlocked with the access doors. Electrical plugs, both from normal and UPS supply, are placed along the clean room walls together with LAN net plugs. The NOA infrastructure has been built with selected materials to reduce radon gas emanation and diffusion; moreover, the air ventilation system has been designed to be compatible with a radon abatement system to supply air to the clean room with a low radon concentration. The combination of these features would make NOA a radon-free environment for packaging photodetectors and electronic devices, with an expected gas concentration reduced by at least of a factor 100. A radon-free environment is crucial for rare event experiments to avoid the plate-out of $210^{210}Pb$, which is a proxy of $222^{222}Rn$. Values less than 1 Bq/m^3 should be achieved to reduce this contamination in detector components assembled inside the clean room [8]. Existing radon-free clean rooms have achieved levels between 10 and 500 mBq/mm^3.

3 Production machines

The CR3 area has been equipped with sophisticated machines dedicated to the cryogenic characterization, handling, packaging, and test of large-area Si-based devices:

- FormFactor PAC200 (https://www.formfactor.com/product/probe-systems/wafer-multi-chip-cryogenic-systems/pac200/), a semi-automated probe station for wafers and substrates in a high vacuum environment, for testing devices at cryogenic temperatures down to 77 K;
- Advanced Dicing Technology 7122 (www.adt-dicing.cn/home/product/info?id=450), an automatic wafer dicer for dicing Si wafer or other thin substrates with high accuracy;
- AMICRA NOVA PLUS Flip Chip Bonder (https://amicra.semi.asmpt.com/en/products/die-flip-chip-bonder/nova-plus-die-bonder-und-flip-chip-bonder/), a modular machine with a precision die attach method for micro-assembly applications;
- HESSE BJ855 (https://www.hesse-mechatronics.com/en/products/fine-wire-bonder/bj855/), a high-speed fully automatic wire bonder;
- Ultron semiconductor assembly systems (https://www.ultronsystems.com/USI-Products.html);
- Two microscopes with different magnifications for device visual inspection to assess possible damages or defects.

A part of CR3 has been devoted to the testing and characterization of the assembled devices and the related electronics: small dewars with sealed flanges, equipped with input/output and vacuum tight feedthroughs and provided with a mechanical structure to hold the devices, are available together with the related instrumentation in order to perform test measurements and data acquisition and analysis both at room temperature and in liquid nitrogen.

3.1 Cryogenic probe system

FormFactor PAC200 (Figure 3) represents a robust platform for performing electrical tests of integrated circuits at the wafer level, performing automatic testing of wafers and substrates up to 200 mm in a cryogenic environment down to 77 K. The probe plate is designed to mount a high-pin count probe card that can be thermally anchored to a cryogenic shield to reduce the heat load through the probe needles. The probe card contacts are very soft and short in length and can be numerous, depending on the specific requests. A high-resolution video microscope is mounted on a

FIGURE 3
Left: cryogenic probe station. Right: dicer.

microscope movement with a travel range of 50 mm × 50 mm in the XY direction and 130 mm in the *Z* direction. PAC200 is equipped with a stable, vibration-isolating frame. The chuck and the motorized chuck stage, with 200 mm × 200 mm X–Y travel, theta, and *Z*-axis, are located inside the high-vacuum chamber. A radiation shield covers the movable chuck of the station to establish conditions of 80 K and below. Two separate cooling circuits for the shield and chuck are provided with precise temperature control that ensures stability at 0.1 K. The machine exhibits excellent measurement accuracy and repeatability.

3.2 Dicer

ADT7122 (Figure 3) is a semi-automatic dicer system with an 8” diameter (or 200 mm × 200 mm square area) dicing area. It is an advanced, fully programmable saw for dicing thin materials into smaller pieces with 1-micron accuracy. Typical applications are Si wafer dicing, but it can also be used for other thin materials and substrates such as sapphire, glass, thin film devices, silicon, and many others with the proper choice of blade type.

3.3 Flip chip bonder

ASMPT AMICRA Nova Plus (Figure 4) is an advanced dual-head die bonding system capable of achieving placement accuracy down to few microns while bonding at temperatures exceeding 350°C and applying high bonding forces. This type of die bonding can be classified as thermo-compression bonding, and in some cases, these capabilities are required for different applications like the through-silicon vias (TSVs). Some tools of the machine have been developed for custom applications requiring the placement and bonding of large-size silicon dies (11.7 mm × 7.9 mm) on a PCB substrate using soft solder paste. A wafer magazine has been provided for die loading, while substrate loading can be done manually. The modular concept of the machine allows for enough flexibility to be upgraded to perform different processes like 3D/2.5D interconnections, TSVs, chip on chip, chip on wafer, chip on substrates, and optoelectronics.

3.4 Wire bonder

Bondjet BJ855 (Figure 4) is a fully automatic ultrasonic fine wedge–wedge fine wire bonder. BJ855 fulfills all wire bonding challenges on one platform. The machine is flexible and can be used with different types of bond heads (included in the machine equipment) to create bonds based on different process technologies:

- Bondhead BK06: designed for thin wire processes according to the wedge–wedge process
- Bondhead DA06: deep access with a compact design, available for bonding inside difficult-to-access devices or tight packages, providing a cavity access of 14.5 mm with a 1-inch wedge tool length. The pivot-free transducer suspension guarantees a constant vertical wedge alignment.
- Bondhead BW01: developed for gold wire processes for the ball–wedge bonding method.

Bonding wires can be positioned precisely on the large, 305 mm × 410-mm, working area. Multilevel bonding is made possible with the 32-mm *Z*-axis lift. Several bond stations can be placed within the working area to enable a high throughput. A permanent real-time monitoring process is in operation during the bond process, monitoring wire deformation, transducer current, frequency, and impedance within a programmable tolerance range. The system can be used in fully automatic and manual operations.

FIGURE 4
Left: flip chip bonder. Right: wire bonder.

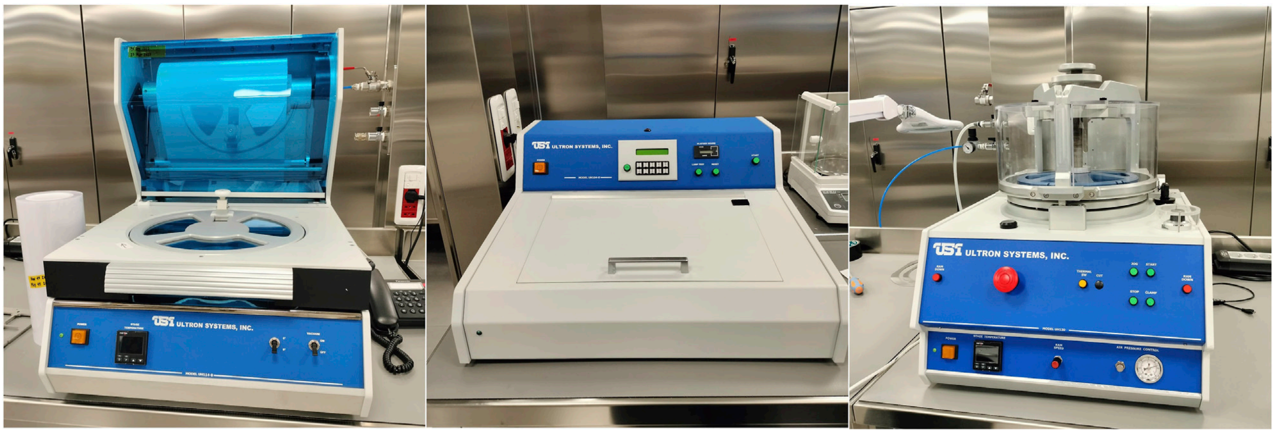

FIGURE 5
Manual packaging tools. From left to right: tape release, UV curing, and wafer expander.

To evaluate the strength and reliability of wire bonds, a high-quality and compact pull-tester unit (LAB-Tester LT-101), equipped with most up-to-date software and available for thin and heavy wire applications, is available inside NOA.

Two microscopes with different objective magnifications are also available for optical inspection and quality control of the devices.

3.5 Semiconductor assembly systems

NOA CR3 has also been equipped with a set of semiconductor assembly systems (Figure 5) for frame film mounting, ultraviolet (UV) curing, and die expansion to handle silicon wafers.

- Ultron Model UH114 accommodates up to 8-inch (200 mm) wafers/film frames to hold the wafer during the dicing/sawing operations, where uniform adhesive plastic film lamination is crucial. The unit features a retractable film-cutting system with adjustable cutting pressure to accommodate various tape base materials and different thicknesses. Roller pressure is adjusted from the topside of the unit for different process requirements and to accommodate various wafer thicknesses;
- Ultron Model UH104 UV tape exposure accommodates up to an 8-inch grip ring or film frame-mounted wafer. It provides uniformity of UV exposure and fast UV curing times using an ozone-free UV lamp array with a cool, low-temperature UV-A 365-nm curing process. Adhesion reduction is necessary to

allow the die-bonding process to pick up every single die, and it is performed before the die-expansion process;
- Ultron UH-132 Motor Drive Die Matrix Expander offers digital speed control for great precision in wafer expansion by producing both linear and uniform expansion throughout the entire drive stroke. This operation improves die handling after dicing in the subsequent die-attaching process.

4 Future perspectives

The NOA clean room at LNGS is a new INFN infrastructure definitively commissioned in February 2023 and designed for the production, testing, and integration of large arrays of SiPMs in a dust-controlled environment with low radon emanation. The current main user of the clean room is the DarkSide-20k collaboration, whose goal is to produce more than 500 SiPM-based photodetection units (PDUs), each sized 20 × 20 cm for an overall surface of 21 m^2 of silicon. Some of the machines have been partially designed, following the DarkSide-20k demands, but they are flexible enough to be upgraded with more commercial tools. The cryogenic probe station can be configured with different probe-card technologies available on the market. The flip chip bonder is one of the most advanced die bonding systems for semiconductor packaging with high placement accuracy, and the bond tools and other custom parts can easily be replaced with new ones with a different design, according to the customer's requirements. The HESSE Wire Bonder is the latest generation of fully automated fine wire bonders. An interesting perspective under evaluation through a feasibility study is the implementation of a radon abatement plant. This upgrade would make the infrastructure unique for the packaging, testing, and assembly of photodetectors in a Rn-free environment. A memorandum of understanding of the infrastructure has been elaborated, collecting the access rules, operating procedures, technical aspects, and plant design of the clean room, with a detailed description of the packaging machines and the cost for running and maintenance. For at least 1 year, NOA will mainly host the DarkSide-20k activities; nevertheless, it is already receiving requests from other research groups interested in the clean room usage and related equipment, demonstrating its intrinsic potential to become a technological hub for the packaging and testing of photodetectors and electronic devices in a controlled atmosphere environment.

Author contributions

LC: writing–original draft. AF: writing–review and editing. AI: writing–review and editing. AM: software and writing–review and editing. LP: writing–review and editing. GP: writing–review and editing. DS: writing–review and editing. RT: writing–review and editing.

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Conflict of interest

The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

The author(s) declared that they were an editorial board member of Frontiers, at the time of submission. This had no impact on the peer review process and the final decision.

Publisher's note

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