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IR vision: from chip to image/Vision IR : du composant à l'image

Infrared technologies characterization in CELAR

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Presented by Guy Laval

Abstract

In this paper, we described the Infrared technologies (MCT, QWIP and microbolometers) characterization carried out by CELAR, in addition to the Electro-Optical (EO) characterization driven by ONERA, both backing up service programs of the French National Armaments Organization (DGA). After a brief description of the methodology and tools used, some results are given in order to show the construction and failure analysis contributions in the correlation of EO defects to visual defects and also, in the quality and preventive reliability improvements for these IR technologies, for a better satisfaction of the military end-users needs. ***To cite this article: P. Burgaud et al., C. R. Physique 4 (2003).***

Résumé

Caractérisation des technologies IR au CELAR. Le présent papier décrit la caractérisation technologique menée au CELAR sur les technologies IR (HgCdTe, puits quantiques et les microbolomètres) au profit des Services de Programmes de la DGA en complément de la caractérisation électro-optique réalisée par l'ONERA. Après une brève description de la méthodologie et des outils, différents résultats illustrent l'apport de l'analyse de construction et de l'analyse de défaillance dans la corrélation des défauts visuels et électro-optiques et dans l'amélioration de la qualité et de la fiabilité préventive des technologies IR pour une meilleure satisfaction du besoin client. ***Pour citer cet article : P. Burgaud et al., C. R. Physique 4 (2003).***

Keywords: Infrared technology; MCT; QWIP; Microbolometers; Construction and failure analysis

Mots-clés : Technologie Infrarouge ; HgCdTe ; Puits quantiques ; Microbolomètres ; Analyses de construction et de défaillance

1. Introduction

Since 1997, the expertise on electronic components in the DGA (French National Armaments Organization) has been centered specifically on the critical components encountered in a weapon system, specially for nondual components. In this context, Infrared technologies are always evaluated at the CELAR (Electronic Warfare Center); this concerns optronic system evaluation as well as component evaluation. Specifically on the IR components evaluation, the CELAR has much experience in the 20 years of its existence, and it supports major armament programs (such as the Hélios II program, for example) and Research & Technologies programs driven by the Strategy on Common Technologies Service of the DGA (STTC).

For this work, the CELAR brings a technological expertise on these components, in complement to the electro-optical characterizations driven by ONERA or other laboratories such as CEA/LETI/LIR, by making:

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- risk analysis, covering technical and calendar solutions given by the component manufacturer, in conformity with the military operational environment;
- control on IR component manufacturing, in order to check the quality, reliability and availability;
- prospecting and monitoring of the technology evolution and improvement, in order to satisfy the near and future military needs;
- help to identify the technologies needed in our weapon systems for improvement in term of technological breakthrough.

To achieve these missions, the CELAR generally characterizes the technology of IR components by construction analysis and failure analysis.

Construction analysis makes possible the determination of the intrinsic potential failures of the technology. Thus, construction analysis is a good tool to prevent failure and improve yield, both reducing the final equipment cost of ownership. This work is driven in closer partnership with component manufacturers in a 'win–win' concept.

Failure analysis is driven with the aim of identifying the cause root of the failure, and takes place during the development of the program (test on demonstrator) and the operating life of the equipment (field return).

We also carry out an audit of the manufacturing line and qualification tests according to the end-user's needs, on the cooled IR technology (MCT, QWIP) or uncooled technology (microbolometer).

This methodology is used world-wide for Si or GaAs technology evaluation, but seems more rarely encountered or detailed for IR technology. In this article, we describe our approach and the tools used for the IR technology expertise in CELAR; furthermore, some results concerning the major failures encountered in our analysis will be shown and discussed.

2. Experiments

The major construction and failure analysis tools for IR technology analysis are identical to those used in current semiconductor technologies (Si or III–V). The Expertise laboratory of CELAR, certified ISO 9001, is equipped of these.

An IR component could be macroscopically described by an sensor (active chip) hybridized on ROIC (Read Output Integrated Circuit) currently by indium bump solder, and this unit is then integrated in dewar cooler. Each of these 3 units and the associated interfaces have to be analyzed.

The first step in the investigation is usually a nondestructive observation by X-ray (X Fein focus FXS-160-23), and optical equipment (e.g., binocular, optical microscope/maximum magnification $\times 1000$) for surface analysis. The separate elements (sensor/ROIC/cryostat) and associated interfaces are then evaluated. The major technological parameters (composition, thickness uniformity, contact etching, step coverage, ...) are determined by cross-section techniques and high resolution Field Effect Scanning Electron Microscope (FESEM) observations performed by a SEM (a LEO 982) equipped with an EDX system (Link PENTAFET) and fluorescence-X (SIM). EBIC measurements are driven with a JEOL 6300 SEM equipped with a Link ISIS system. The composition of materials is defined by Energy Dispersive Spectroscopy-X (EDX). The microsections are made by either classical mechanical polishing or cleaving and with Focus Ion Beam equipment (Schlumberger IDS P3X FIB) in the case of a need for a well-defined area analysis (e.g., the cross section of a little particle). By selective attack or etch of the cross-sectioned sample surface, the different layers and junction are delineated. The surface revelation for SEM observations or layer removal for construction analysis are obtained by wet-etching or dry-etching, following the materials. The CELAR expertise laboratories possess 2 dedicated RIE equipment for either dielectric or metal etching (NEXTRAL NE100 with Ar, O_2, SF_6 and CHF_3 gas, and PLASSYS equipped with the gases just mentioned plus C_2F_6, CL_2 and BCl_3 gas) which covers a large panel of etching gas mixture. Finally, concerning the soldering expertise, we have an acoustic microscope (SONIX HS 1000) and for specific electrical tests, we use a Karl Suss PM5 analytical prober. At liquid N_2 temperature, the electrical tests I(V) are carried out in the SEM chamber in low vacuum.

The performance and the quality of the IR technology are inspected with regard to critical technological parameters and by identification and corrective action of all weak points of the technology. The construction analysis helps us for this purpose, and permits also to elaborate a qualitative and preventive evaluation of reliability, by the determination of potential failure mechanisms. On the other hand, failure analysis is made in order to define the failure mechanism and the root cause.

3. Results and discussion

The 3 majors IR technologies which result from technology characterization shown hereafter are MCT, QWIP and microbolometer IR technologies. All these failure analysis results have been obtained during the development phase of the R&T program, and the defaults shown in this paper are mainly for demonstrative and didactic purpose.

3.1. Hybridization evaluation

For the highest performance, the MCT detectors are cooled to an operational temperature around 80 K, and cryogenic cooling techniques are needed. On this basis, a schematic hybridization between different parts encountered on a MCT or QWIP structure detector is shown in Fig. 1.

Each element and associated interface will be evaluated in our methodology. The detecting element is soldered to the ROIC with indium solderbump at each pixel, and the whole structure is then soldered onto the substrate (sapphire, for example). Then, this module is mounted directly on the cold tip of the cooler and vacuum encapsulated.

A cross-section example on this technological stack is shown in Fig. 2. The defaults observed in the joint solder are numerous voids or holes which are magnified and shown on the zoom of Fig. 2. These defaults will affect the mechanical behavior and fatigue during the temperature cycling due to the thermal mismatch of the materials. Furthermore, as there is no good thermal contact, the performance could be affected also due to the poor thermal conductivity (on the cold down time for example).

As we can see also on Fig. 2, for large Focal Plane Array (FPA) in MCT technology, the standard process of the hybridization is performed with an underfiller and lapping operations of the detector's substrate: the MCT sensor is thinned. The major goal of the underfill is to maintain In-bump soldered module (MCT detector on the ROIC) during the lapping operation but an inadequate underfill process can induce extrinsic defaults in operation life as shown on Fig. 3 (example of failure analysis after EO defect characterization).

In the previous case (Fig. 3), the glue of the underfill has well-filled all interstices of the chip surface, and due to the mismatch between the coefficients of thermal expansion of the materials (MCT, ROIC and underfiller) during temperature cycling, some tensile strengths appeared at the via area and involved cracks in the building layers of the chip, which broke the metal layer underneath the surface.

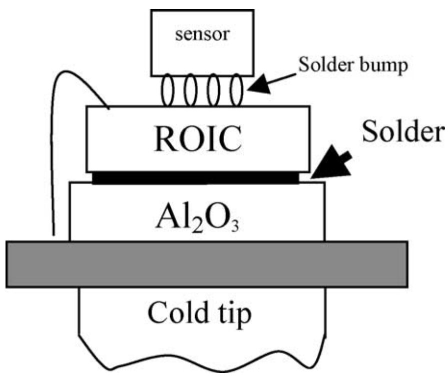

Fig. 1. Schematic of hybridization of a FPA (Focal Plane Array) with CMOS ROIC (not to scale).

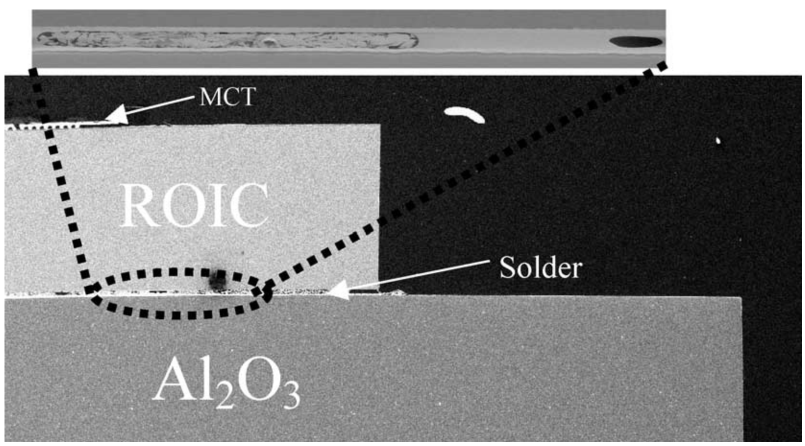

Fig. 2. Cross-section view of hybridization MCT FPA showing a default in the solder joint between the ROIC and the Al_2O_3 substrate.

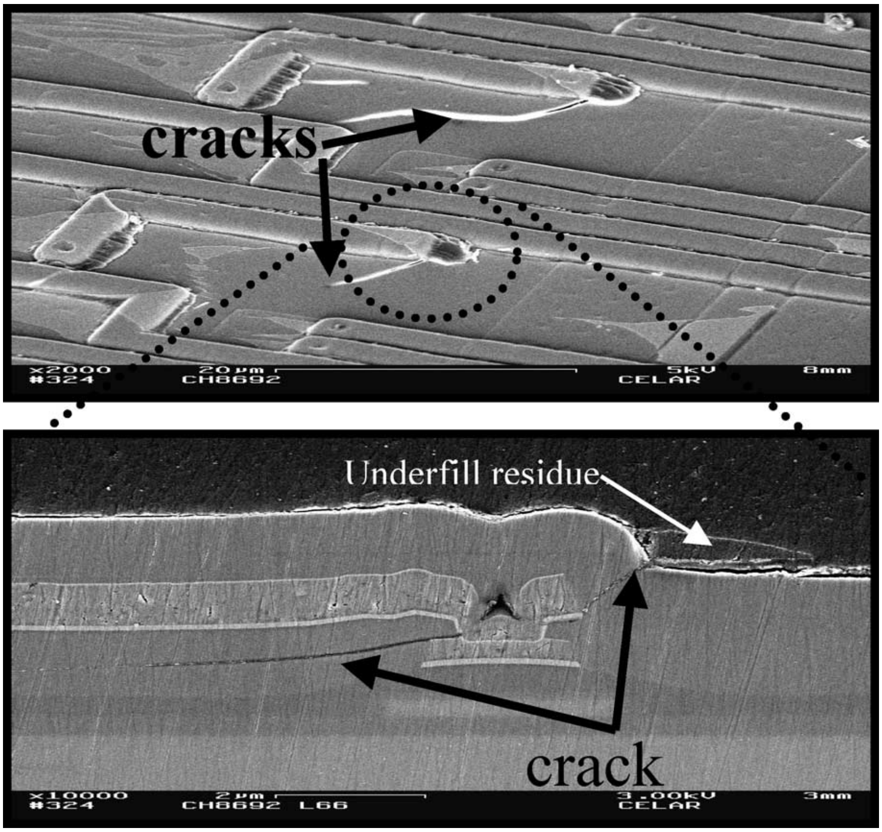

Fig. 3. The upper picture shows different cracks observed on the surface of the ROIC's passivation layer after underfill removal. The lower picture shows a cross-section in the metal via area and we can observe the crack inside the chip, going through the via, inducing open circuit in the ROIC.

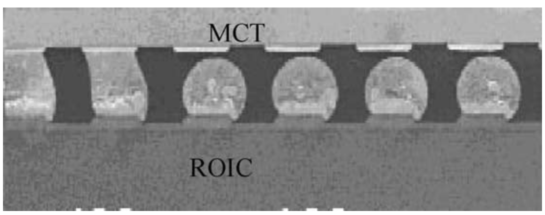

Fig. 4. Cross-section of In-bump soldering between MCT and ROIC showing some In-bumps which did not wet the pad of the sensor and keep the initial shape after the reflow process.

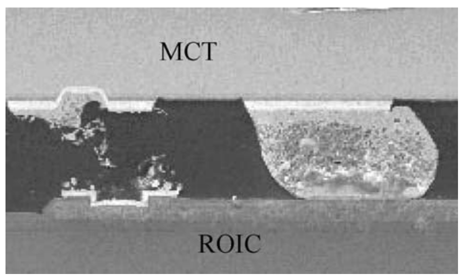

Fig. 5. Cross-section of In-bumps soldering between MCT FPA and ROIC, where a bump (at left side), connected to a diode, is partially dissolved.

The last area of interest in the hybridization evaluation is the solderbump. Some open circuits (i.e., leading no functional pixel) are correlated sometimes with missing solder contact between the ROIC and the sensor pad. Sometimes, the soldering process is found to be responsible (see Figs. 4 and 5) and the electro-optical failure appears at the final test (EO sort).

Figs. 4 and 5 show some defaults occurring undoubtedly during the hybridization process because these defects were trapped by the underfill glue and stayed in their original state. In the case of the default shown on Fig. 4, the root causes can be numerous: bad parallelism of both chips, inhomogeneous bump sizes, bad wetting, ... For the default shown on Fig. 5, the cause root assumption is probably related to an electrochemical phenomena occurring with flux solute.

On the other hand, electro-optical failures corresponding to an open-circuit and which appear in the operation life, would be related to a solderbump failure as shown in Fig. 6, due to the stress occurring with temperature cycling between ambient temperature and operational temperature at 80 K as well.

These last defaults related to hybridization are purely intrinsic defaults and inherent to the In-bump soldering hybridization. Extrinsic defaults are also observed following In-bump hybridization when the MCT process of the chip sensor is not totally controlled and mastered. For example, we have observed some cracks on the surface of a MCT thinned sensor and In- bump hybridized with underfill process.

An investigation driven on this defect area by local cross section with FIB, shows on Fig. 7 that such cracks are always above and near the diode area.

The contact diode via of each pixel is opened from the passivation layer and metal contact are then deposited. A standard metallization bond pad of contact diode is composed generally of 3 layers ensuring: an ohmic behavior to the semiconductor material, a diffusion barrier and a wetting to the solderbump respectively. The last one is generally a thin gold layer. Unfortunately, a bad step coverage of the metal contact diode on the edge of the via, could be responsible of the cracks observed on the MCT thinned surface as shown on Fig. 7. Effectively, during the indium hybridization process, the indium bypassed the barrier metal through the discontinuity due to the bad step coverage, and an intermetallic compound was formed underneath, which lifted the metal layers and broke the passivation layer as shown on Fig. 8. These modifications brought new constraints which favored cracks appearing on the top of the MCT thinned surface involving a killer defect.

This last study shows the great interactivity between the major IR technology cooled processes (MCT or QWIP manufacturing, hybridization and ROIC chip) and their quality dependence.

For this reason, the CELAR evaluates sensor technologies (MCT, QWIP and microbolometer) in depth. Concerning the ROIC technology evaluation, silicon technologies driven by civilian applications are more mature and the failures are rare events; thus the efforts can be released.

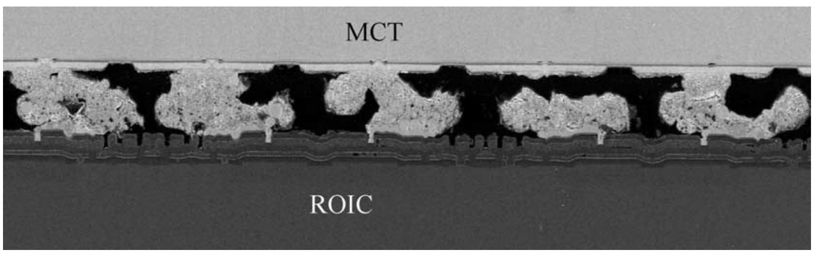

Fig. 6. Shape of In-bumps without underfiller hybridization and thermally stressed after 1000 cycles. Broken bumps failure appear due to stress fatigue and lead to an open circuit.

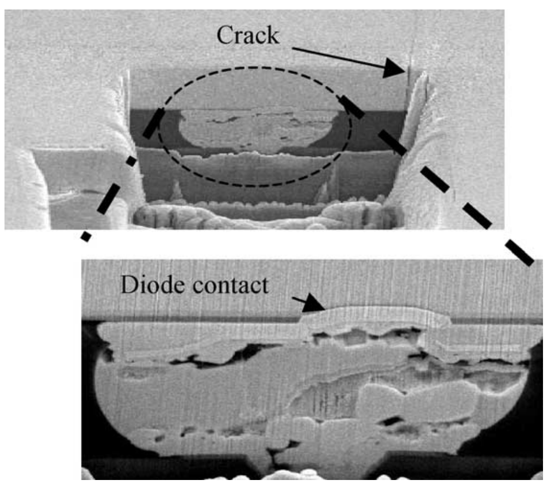

Fig. 7. Cross section with FIB on MCT thinned surface with cracks on the top of the surface. The zoom is magnifying the diode contact area, showing the shape of the In-bump (not to scale) and the delaminating layers of the diode metallization.

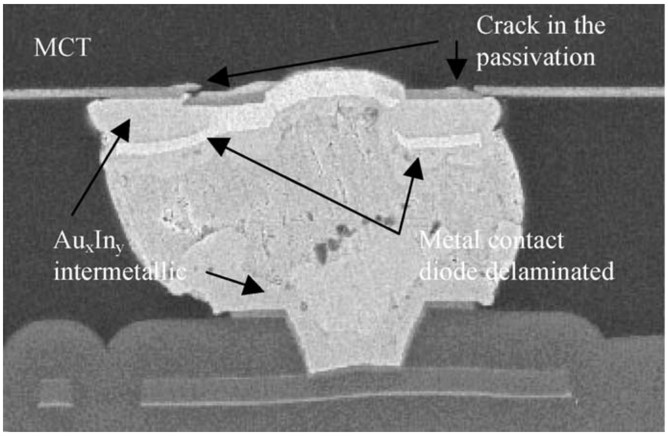

Fig. 8. Cross section on a In-bump showing the delaminating of the contact diode layers and passivation cracking after Indium hybridization with intermetallic formation Au_xIn_y underneath.

3.2. Sensor technology and process evaluation

In this part, the characterization is specific following the IR technologies in use, since the critical parameters are different.

In microbolometer technology, for example shown in Fig. 9, which is based on the Si-technology concept in our case, the major critical elements related to electro-optical performance and reliability are mainly the pixel design and the technological characteristics of the absorbing layer.

In this context, the technological analysis on microbolometer consists of checking essentially the dimensional characteristics (of the membrane, the height of the cavity and the interconnect layer), the surface aspect of the layers (grain size, step coverage, etc., their chemical nature) and the aspect of interfaces between layers (contacts).

From a general point of view, the most important technological parameters are monitored for the whole technology (MCT, QWIP and bolometers) and mainly consist of the thickness of the different layers (metal and epitaxy). A statistical monitoring is performed on die, wafer and sometimes run to run, to assess process quality.

We try to define also the correlation of EO defaults to visual defect carried out with optical microscope and SEM surface analysis. Numerous visual defects (particle, cracks,...) generally encountered in wafer fabrication, are well correlated to specific EO faults (died pixel, short-circuit, open circuit,...). A wafer yield analysis is also performed for a better assessment of cost, global sensor cycle time, and reliability. Both yield and reliability are strictly correlated according to CELAR and users' experiences.

Nevertheless, others EO faults such as defects related to noise, responsivity characteristics, are difficult to correlate to visual defects, and this is particularly observed on the MCT technology. This means probably that the cause root is deeper in the technology or the material (carrier concentration, micro defect,...), and the tools used in our characterization are not suitable.

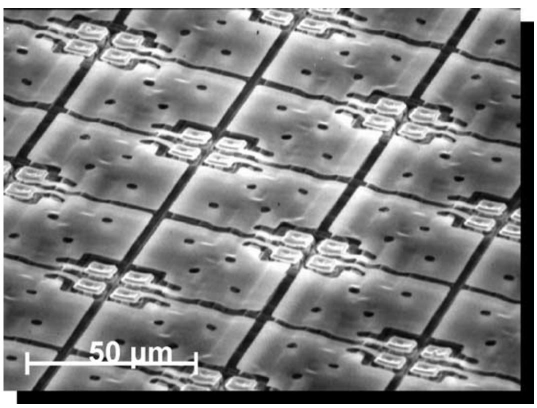

Fig. 9. Perspective view of microbolometer arrays.

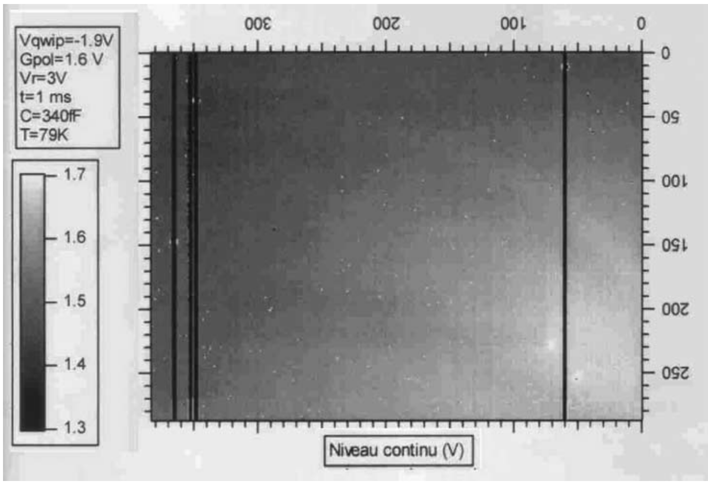

Fig. 10. Spatial distribution of output voltage showing some dead columns.

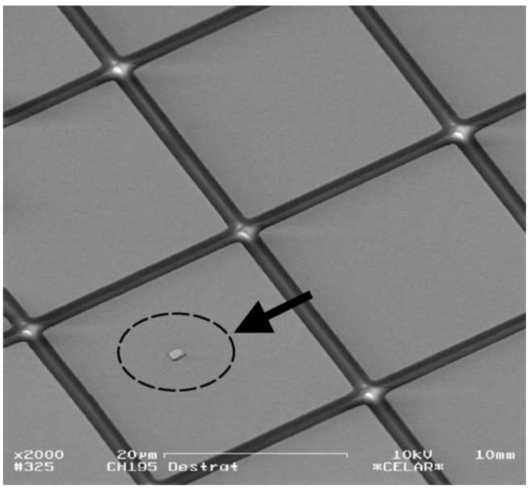

Fig. 11. SEM view of QWIP array after GaAs substrate removal (not to scale). A defect located in the pixel is observed.

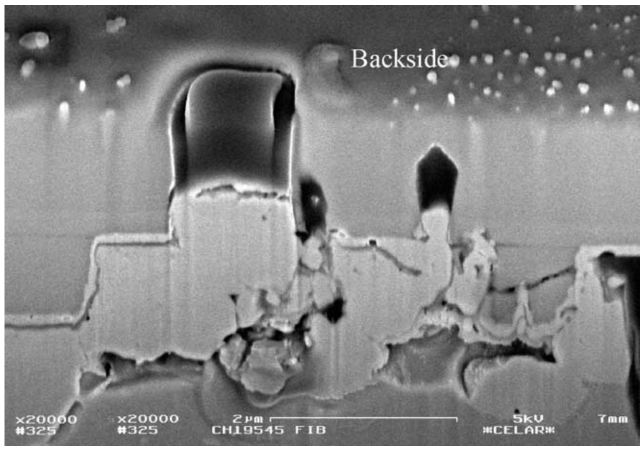

Fig. 12. FIB cross section on the buried defect. The In-solderbump short-circuits the active layers.

We hope to see an improvement by introducing systematically EBIC characterization in our methodology and correlation test on MCT technology.

One example of correlation default is given on the QWIP technology shown on Figs. 10–12. We had to expertise some chips coming from a production line, which presented some short-circuit faults (line, row) on the QWIP array as shown in Fig. 10.

No external visual defect was noticeable on the surface of the chip.

After removing GaAs substrate, we have revealed and identified one single buried defect at each column which bypassed the active layers on a pixel as shown in Fig. 11.

A FIB microsection located on this previous buried default is shown in Fig. 12.

The cause root of this defect was the lifting of a piece of the reflecting grating during the process. The following technological step and In-solderbump hybridization induced a short-circuit in the void left by the piece of reflecting grating missing. An immediate and appropriate corrective action carried out by the manufacturer eliminated this buried defect.

4. Conclusions

The majors results presented and discussed show that Infrared technology characterization, carried out by CELAR, implements with efficiency electro-optical characterization and contributes to determine process weaknesses, reliability concerns and special features of the IR technology regarding our applications. The construction and failure analysis bring a noticeable improvement in the correlation of EO defects to visual defects and also in the quality and preventive reliability improvements of the IR technologies (MCT, QWIP and microbolometers), for a better satisfaction of the military end-users needs.

Some improvements are still expected in the correlation of electro-optical performance to critical technological parameters.

Due to the recent use of technology in an operating environment, the field return is not enough today for a sufficient understanding of failure mechanisms during operating life, in order to improve the equipment availability. A Field Failure Return Program could be enhanced this.

Furthermore, in our near future improvements, we will integrate the systems, mandatory in our evaluation, in order to appreciate in depth the defect significance related to system performance.

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