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GaAs Pixel Detectors with Integrated Electronics: experimental basis and feasibility study

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ABSTRACT

This work aims to study the feasibility of the integration, on the same chip, of GaAs pixel detectors and front-end electronics employing GaAs MESFETs or HEMTs. Interest of a full GaAs integrated systems are in X and γ-ray spectroscopy and imaging for scientific, industrial and medical applications. The current status and recent experimental results regarding radiation detectors on semi-insulating GaAs are presented. Measurements of the relevant parameters of GaAs FETs suitable for the stringent requirements of a spectroscopy-graded front-end amplifier are analysed. Some still open problems regarding the detector-electronics integration are highlighted.

I. INTRODUCTION

Gallium Arsenide has a great potential to become the preferential semiconductor for realising detectors and imaging systems for X and γ rays. The higher atomic number with respect to silicon, makes GaAs efficient of about a factor of 20 in detecting X and γ photons with energies above 12 keV. Moreover the GaAs band-gap energy, higher than both the one of silicon and germanium, makes it attractive for the development of detectors with potentially low thermally generated dark current, able to operate at room temperature, so avoiding cumbersome and unpractical cooling systems. For these reasons a big effort has been done in the last few years world-wide for fabricating good quality GaAs detectors for X and γ spectroscopy [1, 2]. Applications of these devices are in the field of industrial and security systems for radiation monitoring and inspection and in the field of medical imaging for diagnostic purposes. With respect to detectors based on other high Z semiconductor as CdTe, CdZnTe and HgI_2 [3], GaAs detectors have the significant advantage to account for an existing well-established microelectronics technology. This property can permit to design and build monolithic multi-channel detectors with a wide variety of geometries and pixel sizes. Moreover, the GaAs technology offers the opportunity to integrate custom front-end electronics directly on the detector chip, with the potentiality of realising compact, high-performant and reliable integrated spectroscopy and imaging system for X and γ rays. In this work we present the results of our research dedicated to the feasibility study of GaAs integrated detection systems.

II. DETECTOR TECHNOLOGY

The detectors were made by Alenia on semi-insulating (SI) Liquid Encapsulated Czochralski (LEC) undoped <100> oriented GaAs substrates supplied by Outokumpu (OTK) and Hitachi (HTC). Dot and pixels detectors were fabricated. The dots have an active area of 7 mm^2 and a thickness of 100 μm. The pixel detector, constituted by a matrix of 6x6 pixels, have been built on a 200 μm thick bulk. The pixel area is 200x200 μm^2. The Schottky contacts were realized on the front surface of the wafer with Ti/Pt/Au metallization by photolitographic processes. The ohmic contact, on the back of the chip, is common to all the pixels. Two different non-alloyed ohmic contact, labeled RI and RA, have been tested [4]. A new ohmic contact, named RB, is under test. The RI ohmic contact was obtained by implanting Si^+ ions at two different doses and energies; a dose of $7x10^{12}$ cm^{-2} at 300 keV and a dose of $1x10^{13}$ cm^{-2} at 40 keV. The wafers, capped with SiN, were then fast annealed at 850 °C. The RA ohmic contact was obtained with a particular surfaced treatment by means of polishing, chemical etching and ion bombardment processes. Finally the metal contact was achieved by alloying an e-beam deposited Au/Ge/Ni multilayer at 420 °C for 30 s in $N_2 + H_2$ (10%) atmosphere.

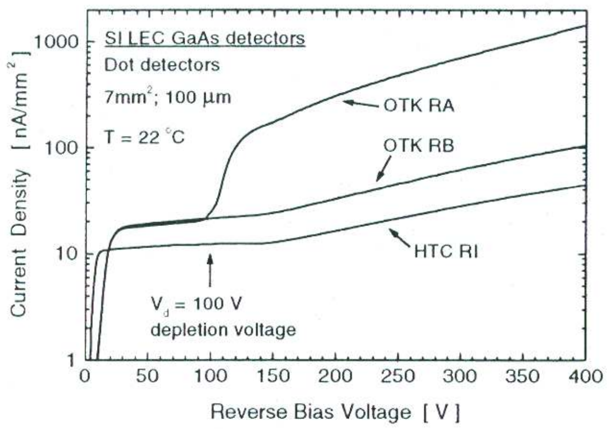

Fig. 1 Current densities of X-γ ray detectors built on Semi-Insulating LEC GaAs bulk. Different ohmic contact technologies (RI, RA, RB) have been tested.

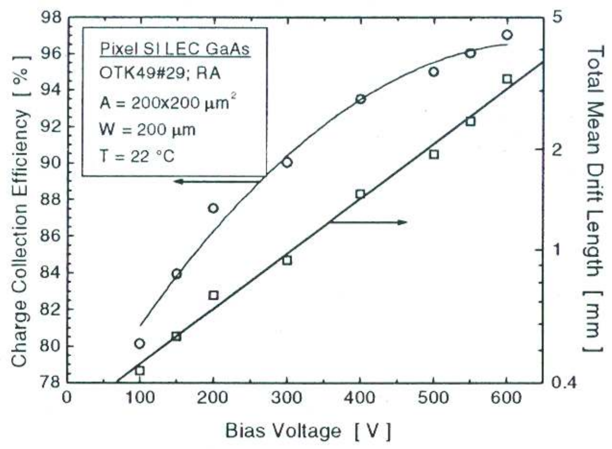

Fig. 3 Charge collection efficiency of the pixel detector measured for the 59.54 keV γ-ray of ^{241}Am at room temperature.

III. Experimental Tests of Detectors

Several previous works have highlighted that the performance of GaAs detectors are presently limited by the starting material quality and by the technological process [4-6]. In particular, two important parameters have to be analyzed to test the detector quality: the dark current and the mean drift length of electrons and holes. Figure 1 reports the dark current density of GaAs measured with dot detectors employing different technological process for the ohmic contacts. It has been also determined that the dark current decreases of about one order of magnitude every 20°C of temperature decreasing. The shot noise associated to the reverse current presently constitutes a limit to the energy resolution achievable with the GaAs detectors. In Fig. 2 it is shown the calculated contribution of the reverse current to the noise performance of a GaAs detector, assuming as variable and parameter the detector area and the operating temperature, respectively. The evaluation has been done considering a typical current density of 20 nA/mm^2 and an RC-CR signal filtering. From Fig. 2 it can be derived that pixel detectors with areas below 0.1 mm^2 can potentially achieve good energy resolution (< 1 keV FWHM) even if operated at room temperature. Obviously, the overall noise performance is also influenced by the front-end amplifier noise characteristic, so that the data in Fig. 2 gives only the inferior limit of the performance, as set by the detector.

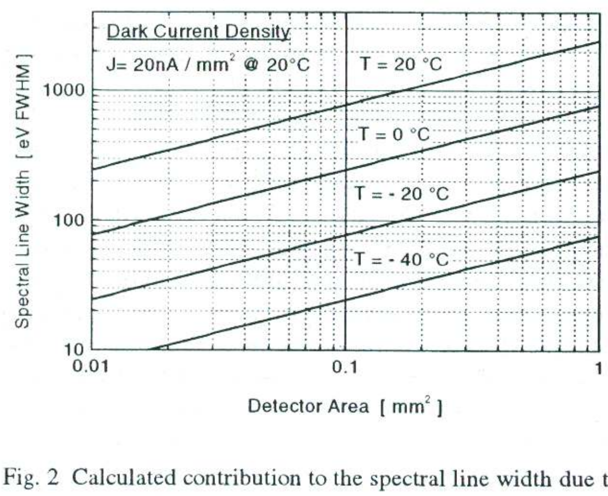

Fig. 2 Calculated contribution to the spectral line width due to the shot noise of the detector dark current.

Another important parameter characterizing the GaAs detectors is related to the trapping of the charge carriers. It is experimentally observed that, differently from silicon or germanium detectors, in GaAs a non negligible fraction of the charges generated by the photon are trapped before they can reach the detector electrodes. It has been observed that the detrapping time is longer than commonly used signal processing time (0.25 µs-3 µs). The trapping produces a lost in the signal amplitude with a consequent degradation of the signal to noise ratio. Moreover it has been recently proven that trapping phenomena are also responsible for a significant broadening an distortion of the spectral lines [7]. The charge trapping can be evidenced by measuring the so called Charge Collection Efficiency (CCE), defined as the ratio between the electric charge induced at the detector output electrode and the charge generated by the photon. In Fig. 3 it is shown the CCE of a GaAs pixel detector measured at different bias voltages. As can be seen a CEE as high as 97% can be reached with a proper applied bias. From CCE measurements the mean drift length of electrons and holes before being trapped has been evaluated and it is shown in Fig. 3 (right y-axis). The mean drift length is related to physical parameters as the trap concentration, the trapping cross section and the mean drift velocity of the carriers [7]. The highest drift length is required for both electrons and holes in order to achieve a CCE as high as possible. The mean drift lengths of the carriers set a limit to the maximum thickness (W) of the detector. In fact, as shown in Fig. 3, a drift length of more than 10W is required to reach a $CCE > 90\%$.

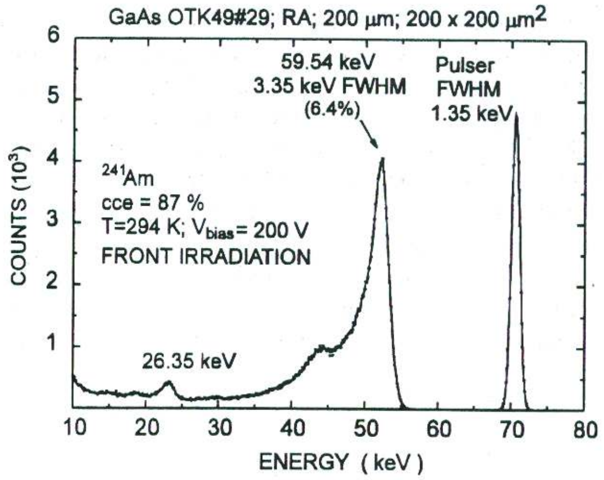

Fig. 4 Room temperature ^{241}Am spectrum acquired with the GaAs pixel detector.

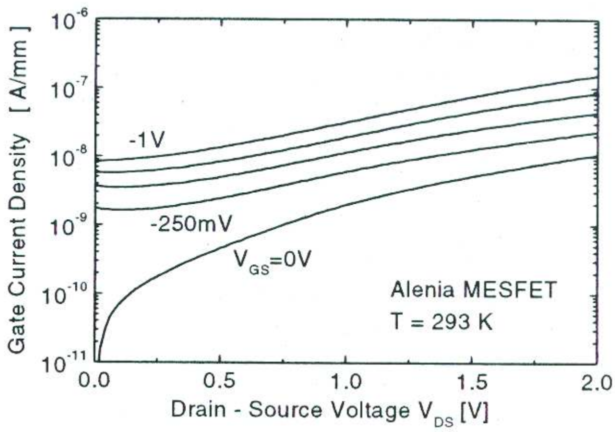

Fig. 6 Measured gate leakage current density (per unit gate width) of Alenia MESFETs.

In order to test the spectroscopic capabilities, a GaAs pixel detector has been connected to a low noise spectroscopic-graded electronics, employing a state of the art charge amplifier with an intrinsic noise of less than 20 electrons r.m.s.. In Fig. 4 the spectrum of the 59.54 keV photons from ^{241}Am is shown. The spectrum has been acquired with the detector and amplifier operated at room temperature. The measured resolution of 6.4% FWHM at 60 keV represents the best results ever achieved with a detector built on SI LEC GaAs. It can be observed an asymmetry in the spectral line due to a tail in its left side. This distortion from the ideal gaussian line shape is due to the trapping of the signal charges.

Although the presented experimental results proves that pixel GaAs detectors are presently adequate to be employed in X and γ ray spectrometers and imaging systems, even better performance could be achieved by reducing the detector dark current and the trap concentration in LEC GaAs. These will allow to use thicker detector, gaining in detection efficiency, which is an important figure of merit for fast imaging systems.

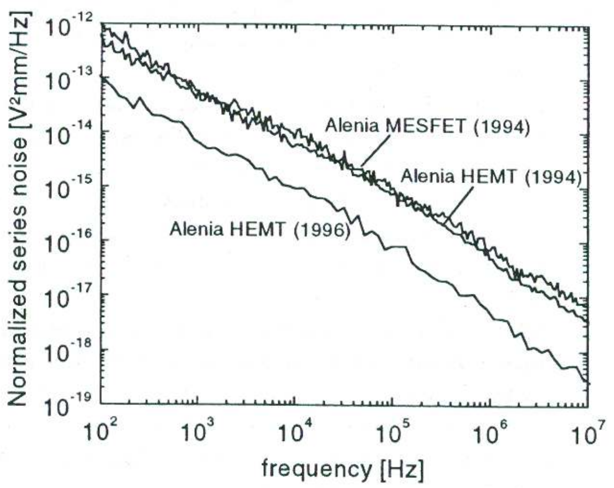

Fig. 5- Normalised series noise spectra of Alenia MESFETs and HEMTs.

IV. FRONT-END ELECTRONICS

Previous researches have proven that GaAs FETs' (MESFETs' and HEMTs') can show excellent performances as front-end devices for radiation detectors [8-10]. In particular, the high cut-off frequency of GaAs FETs makes them even competitive with respect to silicon transistors when short signal processing times (below some tens of nanoseconds) are employed [11]. It has been determined that the main factor limiting the noise performance of GaAs amplifiers for radiation detectors is the low frequency series noise (1/f and Lorentzian). Moreover it has been observed that the low frequency noise is strongly dependent on the technology [12].

Several MESFETs and HEMTs produced by Alenia have been characterised in order to extract the relevant parameters for the design of the front-end and to evaluate the achievable resolution of a GaAs-based integrated radiation detection system. Particular attention has been devoted to the measurement of the low frequency series noise and an improvement in noise performances up to one order of magnitude has been observed during the years. A normalised to gate width A_F factor below 4×10^{12} V^{2}mm has been measured on the most recent HEMT prototypes (Fig. 5). From the experimental data of Fig. 5 and considering a pixel detector, coupled to a front-end, having a total capacitance equal to 0.1pF, it can be evaluated that the contribution of the 1/f noise ranges between 15 and 50 electrons r.m.s. (150-500 eV FWHM).

Another relevant parameter to be considered in a low-noise front-end FET is the gate leakage current. This current constitutes a noise source that can be directly compared with the one associated to the detector dark current. In Fig. 6 the gate current density (per unit gate width) of Alenia MESFETs operated at room temperature is shown. From the experimental data it can be derived that, with a suitable choice of the front-end transistor gate width and bias point, the gate current can be kept below 1 nA adding a noise contribution

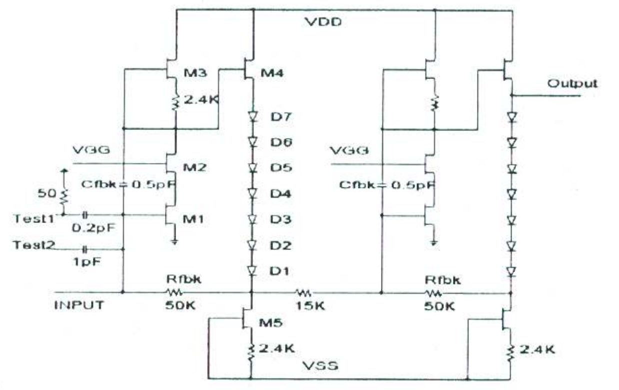

Fig. 7 - Schematic of the charge preamplifier circuit based on Alenia MESFETs.

comparable or even lower than that one of the detector dark current.

Another technological issue to be pursued in developing a GaAs detection system is related to the integration of a low noise reset technique for the charge preamplifier. The classical solution uses a resistor shunting the feedback capacitor. It can be shown that a 50 MΩ resistor adds the same noise contribution as 1 nA detector dark current, and even higher resistances are needed if lower noise are required. The integration of such high resistances can constitute a serious difficulty and alternative reset mechanism are under studied.

Finally, we present a first prototype of MESFET based fully integrated amplifier designed for radiation detectors and produced by Alenia. This amplifier was actually designed as front-end for relativistic particle detectors, but it can constitute a basis for the development of a spectroscopy-graded amplifier. The schematics is shown in Fig. 7. It is composed of a cascade of two feedback amplifiers, the first one acting as a charge preamplifier and the second one as a filter set to give an RC-CR shaped output pulse with a 20ns peaking time. Each feedback amplifier is characterised by a gain-bandwidth-product of 1GHz and a power dissipation of about 5mW. The noise of the amplifier was measured to be $ENC \approx 800$ electrons r.m.s. with a 1pF detector capacitance. The noise of this prototype is strongly limited by the low frequency series noise of the 1994 Alenia MESFETs as well as by the thermal noise of the feedback resistor, whose value is only 50 kΩ. The most recent low noise HEMTs from Alenia can be used in the front-end which will be integrated with the detector. With these new HEMTs and a suitably designed reset system, a noise performance below 100 electrons r.m.s. can be expected with the front-end coupled to a 100fF pixel detector.

CONCLUSIONS

Pixel radiation detectors made on semi-insulating LEC GaAs and coupled to discrete front-end electronics have shown good performances for X and γ ray spectroscopy. It is expected that comparable or even better performances can be achieved by integrating a GaAs-FET front end electronics on the same chip of the detector. From the measurements of the noise parameters of MESFET's and HEMT's made by Alenia, a noise level below 100 electrons r.m.s. (1 keV FWHM of spectral line width in GaAs) can be evaluated. The detector-integration step, possible from a technological point of view, needs the developement of an integrated compact and low-noise reset device for the charge preamplifier.

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