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Performance Evaluation of the Timing Resolution of an AC-LGADs Bonded to a Si-Ge BJT ASICs

Issei Horikoshi,[a,*] Koji Nakamura,[b] Yua Murayama,[a] Koji Sato,[a] Lorenzo Paolozzi,[c] Carlo Fenoglio[c] and Mateus Vicente Barreto Pinto[c]

[a] *University of Tsukuba,*
1-1-1 Tennodai, Tsukuba, Ibaraki, 305-8571, Japan

[b] *Institute of Particle and Nuclear Studies, High Energy Research Organization (KEK),*
1-1 Oho, Tsukuba, Ibaraki, 305-0801, Japan

[c] *University of Geneva,*
24, rue du Général-Dufour, CH-1211 Genève 4, Switzerland

E-mail: horikoshi@hep.px.tsukuba.ac.jp, Koji.Nakamura@cern.ch

Reconstructing particle tracks in future high-luminosity collider experiments is expected to be challenging due to the huge pile-up tracks. 4D tracking by the inner tracking detectors with both spatial and timing resolution will provide reliable track reconstruction. Capacitive Coupled Low Gain Avalanche Diodes (AC-LGADs) developed by KEK, Tsukuba group with Hamamatsu Photonics K.K. have an excellent timing resolution (~20 ps) with 20 µm active thickness as well as a 100 µm×100 µm pitch pixelated electrodes to achieve O(10 µm) spatial resolution. To read out the pixelated AC-LGAD sensors without degrading timing performance low noise and low power consumption ASIC is required. In this study, as a possible candidate of AC-LGADs read out ASIC, a silicon-germanium (Si-Ge) based ASIC, featuring low power consumption, low noise, and high-speed operation has been tested. In this paper, the timing resolution of Si-Ge ASIC bonded to the AC-LGAD sensors by wirebonds and flip-chip is evaluated by using a IR laser and a 3 GeV electron beam at KEK, Japan.

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1. Introduction

In the future high-luminosity collider experiment, particle track reconstruction using only space point will become challenging because of the increase in the number of particle interactions per bunch crossing and underling events. Therefore, timing detectors with high electrode granularity, which have excellent spatial and timing resolutions, can be used to reject pile-up events using 4-dimensional (4D:space and time) tracking [1]. Capacitive-coupled Low Gain Avalanche Diode detectors (AC-LGADs) have been developed in collaboration with Hamamatsu Photonics K.K. (HPK) [2], achieving a timing resolution of 20 ps in a test beam measurement at FNAL with 120 GeV/c protons [3]. In addition, a pixelated AC-LGAD detector with a pitch of 100 µm has been developed, demonstrating a good pulse height response [4].

A readout ASIC for AC-LGADs must provide low jitter (<30 ps) and low power consumption (<1 W/cm^2) to enable a low-mass cooling design for the inner tracking detector. To develop such a readout ASIC, we investigated the potential of silicon–germanium (Si-Ge) based bipolar junction transistor (BJT) technology using a test chip of Si-Ge BJT ASICs [5]. In this paper, we present results of AC-LGADs connected to the ASIC using both wire bonding and anisotropic conductive film (ACF) bonding technology. Performance was evaluated using the analog outputs from the fast amplifier and the two-stage analog driver in the Si-Ge BJT ASIC.

2. AC-LGAD sensors

The LGAD detector is an n$^+$-in-p silicon semiconductor device with a gain layer formed by implanting p$^+$ dopants with a high acceptor concentration beneath the n$^+$ implantation. This gain layer creates a localized high electric field, which induces avalanche multiplication. As a result, LGADs can produce large signals due to the generation of a large number of electron–hole pairs [6]. Moreover, the signal exhibits a faster rise time because the electron–hole pairs are accelerated by the electric field. Therefore, LGAD detectors are capable of achieving excellent timing resolution.

The conventional LGAD detectors have inactive regions between electrodes, and this issue becomes more critical as the electrode granularity increases to improve spatial resolution. A capacitive-coupled LGAD detector (AC-LGAD), shown in Figure 1, has been developed to address this problem [2]. The AC-LGAD provides high-granularity electrode detectors without inactive regions and ensures a uniform high electric field, since a continuous gain layer is implemented independently of electrode size, and signals are capacitively read out through the oxide layer. In fact, we have developed an AC-LGAD pixel sensor with an electrode pitch as small as 100 µm, shown in Figure 2 [4], successfully achieving a detector with excellent spatial and timing resolution.

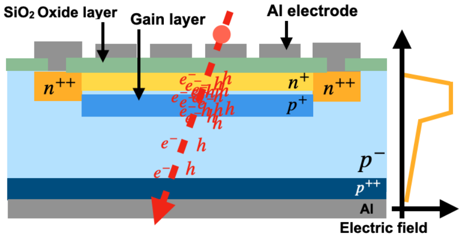


Figure 1: Structure of AC-LGAD.

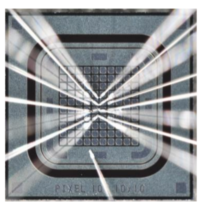
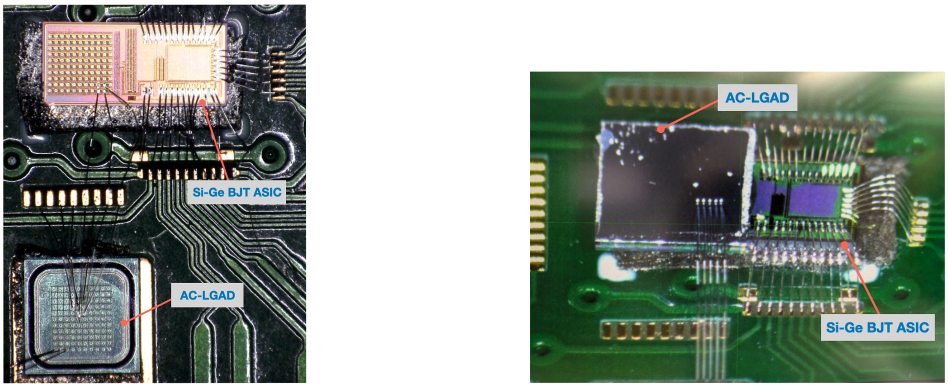


Figure 2: AC-LGAD pixel sensor with wire bonding.

3. Si-Ge BJT ASIC

A silicon–germanium (Si-Ge) based BJT ASIC was fabricated using heterojunction bipolar transistor (HBT) technology in the 130 nm SG13G2 process by IHP. The Si-Ge HBT technology enables the development of front-end circuits with very fast response, low noise, and low power consumption. The Si-Ge ASIC has been shown to achieve a timing resolution of approximately 20 ps with a silicon detector without an internal gain layer [7]. The Si-Ge BJT ASIC test chip used in this study was designed to evaluate various external particle sensors [5]. The ASIC matrix contains 100 electrodes with a pixel pitch of 100 µm, and provides analog outputs from the fast amplifier and the two-stage analog driver. To evaluate performance, we measured an AC-LGAD wire-bonded to the Si-Ge ASIC, as shown in Figure 3a, using an infrared (IR) pulsed laser to assess jitter, and an ACF flip-chip bonded sample, shown in Figure 3b [8], using a 3 GeV electron beam.



(a) AC-LGAD wire-bonded to the Si-Ge ASIC.

(b) AC-LGAD ACF-bonded to the Si-Ge ASIC.

Figure 3: Overview of the connection between the AC-LGAD sensor and the Si-Ge BJT ASIC test chip: (a) wire bonding for the IR laser measurement, and (b) ACF bonding for the test beam measurement.

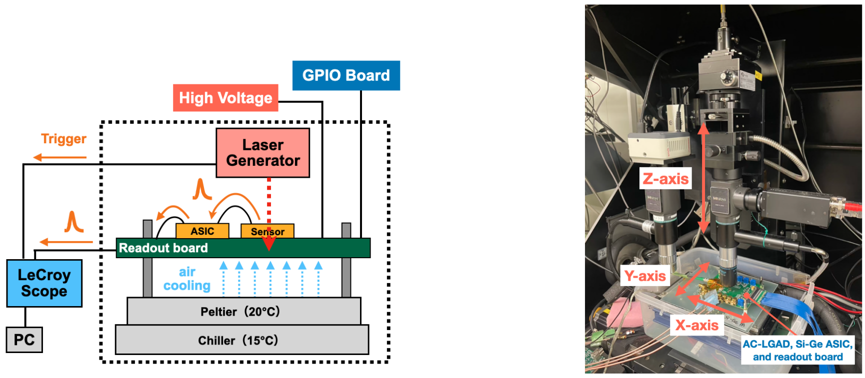
4. Measurement setup

4.1 IR laser measurement setup

The jitter of the Si-Ge ASIC was evaluated using an infrared (IR) pulsed laser manufactured by NKT Photonics K.K. with a wavelength of 1064 nm. The IR laser system deposits energy uniformly across the detector depth, allowing us to measure the intrinsic ASIC jitter independent of charge creation fluctuations in the sensor. The injection point and focus of the laser were adjusted by moving the XYZ stage. The IR laser could be focused to a spot size of 2 µm×2 µm, except in regions covered by aluminum, where the laser was reflected. The signals were recorded using a LeCroy Waverunner 8000HD oscilloscope, with trigger signals synchronized to the IR laser pulse exhibiting a jitter of less than 10 ps.

4.2 Test beam setup

The flip-chip sample bonded using ACF was evaluated with a 3 GeV electron beam at the Photon Factory Advanced Ring (PF-AR) test beam facility of KEK. A schematic diagram of the



(a) Setup of IR laser measurement.

(b) Photograph of IR laser system.

Figure 4: (a) Setup of the IR laser for jitter measurements; (b) photograph of the IR laser with a wavelength of 1064 nm. The injection point and focus of the laser can be adjusted by moving the XYZ stage, and the focus can be narrowed to approximately 2 µm.

setup is shown in Figure 5. Seven layers of silicon pixel detectors, called "telescope", were used to reconstruct the trajectory of incident electron, to compare with the hit position of the detector under test (DUT). The trigger signal was generated by the coincidence between a scintillator hit and the region of interest (ROI) in the second-layer silicon pixel detector telescope. The pulse height distributions of the AC-LGADs were obtained by applying a position cut of 60 µm×60 µm for the 100 µm×100 µm pitch electrode.

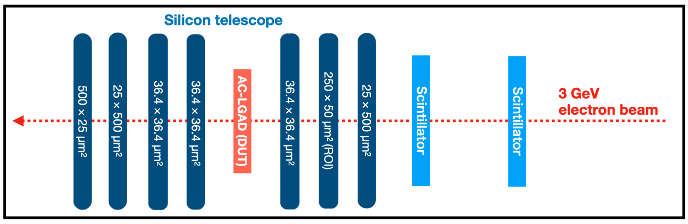
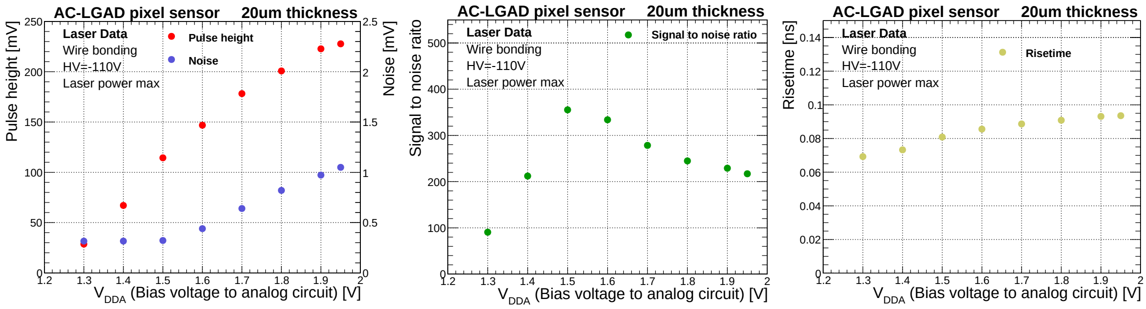


Figure 5: Diagram of the test beam setup for tracking. The numbers in the figure indicate the pixel size of each silicon telescope. The trigger signal was generated by the coincidence between the scintillator and the region of interest (ROI) in the second-layer silicon detector telescope.

5. Results

5.1 Measurement of the wire-bonded sample

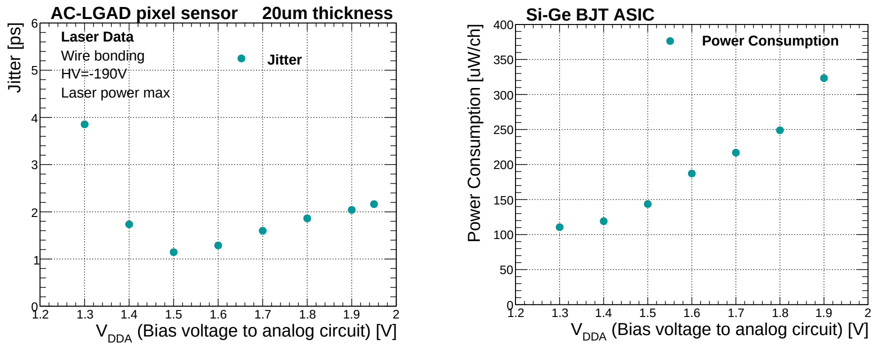
The sensor used in this measurement is an E600-type AC-LGAD, defined in [2] with an n^+ sheet resistivity of 1600 Ω/□ and an electrode capacitance of 600 Ω/mm^2. The device has a thickness of 20 µm and a pixel pitch of 100 µm. The IR laser output was set to its maximum, corresponding to a signal approximately 5.2 times larger than that generated by a minimum ionizing particle (MIP) in silicon. Figure 6a shows the pulse height and electronic noise as a function of the analog bias voltage to the ASIC (V_{DDA}). The pulse height increases with V_{DDA}, reaching ~230 mV at the maximum voltage (1.95 V). The noise remains nearly constant at ~0.3 mV up to V_{DDA} = 1.5 V, but begins to increase beyond this point. Compared with the discrete amplifier used in previous AC-LGAD measurements, which had a noise level of 4.8 mV as detailed in Fig. 6 of [2], the Si-Ge ASIC demonstrates a significantly lower noise level. Figure 6b shows the dependence of the signal-to-noise ratio (S/N) on V_{DDA}. The highest S/N was obtained at V_{DDA} = 1.5 V, approximately 2.4 times higher than that of the discrete amplifier. Figure 6c shows the dependence of rise time on V_{DDA}, where the rise time is defined as the interval between 40% and 60% of the pulse height. At lower V_{DDA}, the rise time is slightly faster, with results showing a factor of 1.8 improvement compared to the discrete amplifier.



(a) V_{DDA} vs Pulse height and Noise **(b)** V_{DDA} vs Signal noise ratio **(c)** V_{DDA} vs Risetime

Figure 6: Dependence of (a)the pulse height and noise, (b)S/N, and (c)rise-time on V_{DDA}. The sensor is the AC-LGAD with a thickness of 20 µm, which is connected to the Si-Ge ASIC using wire bonding.

Figure 7a shows the dependence of the jitter on V_{DDA}. The lowest jitter is obtained at V_{DDA} = 1.5 V, which is approximately 3.6 times smaller than that of the discrete amplifier, due to improvements in both S/N and rise time provided by the Si-Ge ASIC. Figure 7b shows the dependence of the preamplifier power consumption on V_{DDA}. The Si-Ge ASIC preamplifier consumes 144 µW per channel at V_{DDA} = 1.5 V, which corresponds to the operating point with the lowest jitter.

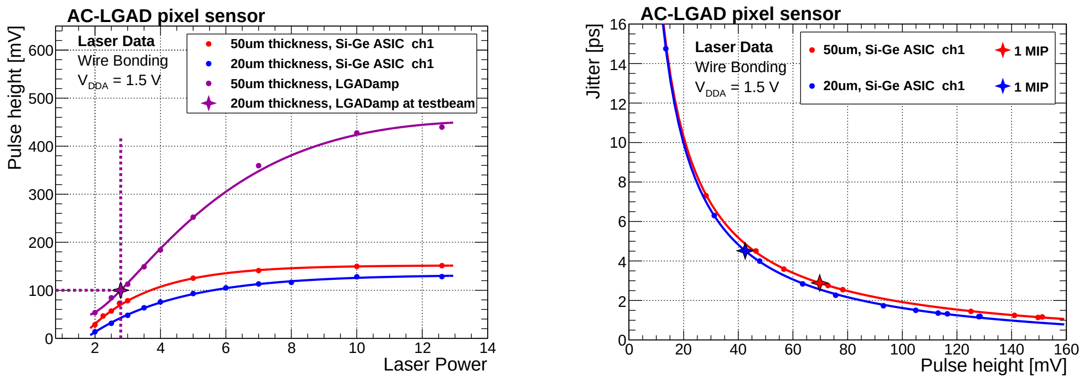


(a) V_{DDA} vs Jitter **(b)** V_{DDA} vs Power consumption

Figure 7: Dependence of (a)the jitter and (b)power consumption on V_{DDA}. The sensor is the AC-LGAD with a thickness of 20 µm, which is connected to the Si-Ge ASIC using wire bonding. The IR laser power is set to its maximum. The power consumption shown here corresponds to the preamplifier only.

To calibrate the IR laser power to a level equivalent to a minimum ionizing particle (MIP) signal, the dependence of pulse height on laser power was measured by varying the ND filter attenuation. The results are shown in Figure 8a. In this measurement, V_{DDA} was set to 1.5 V to evaluate the optimum performance of the Si-Ge ASIC. The results obtained with the Si-Ge ASIC connected to AC-LGADs with thicknesses of 20 µm and 50 µm are shown by the red and blue lines, respectively. In addition, the result obtained with the discrete amplifier connected to the AC-LGAD is shown by the purple line. The cross marker indicates the pulse height corresponding to an MIP, measured using the discrete amplifier connected to the AC-LGAD, which is about 100 mV. Therefore, the laser power corresponding to an MIP is determined to be 2.8. Moreover, the pulse heights of the Si-Ge ASIC connected to the AC-LGADs with thicknesses of 20 µm and 50 µm are 43 mV and 70 mV, respectively.

Figure 8b shows the dependence of the jitter on pulse height to investigate performance under MIP-equivalent conditions. The cross markers indicate results obtained with the Si-Ge ASIC under MIP-equivalent conditions. These results show that the jitter of the Si-Ge ASIC is 2.9 ps when connected to the 50 µm-thick sensor and 4.5 ps when connected to the 20 µm-thick sensor. A summary of the IR laser measurements is provided in Table 1.



(a) Laser power vs Pulse height

(b) Pulse height vs Jitter

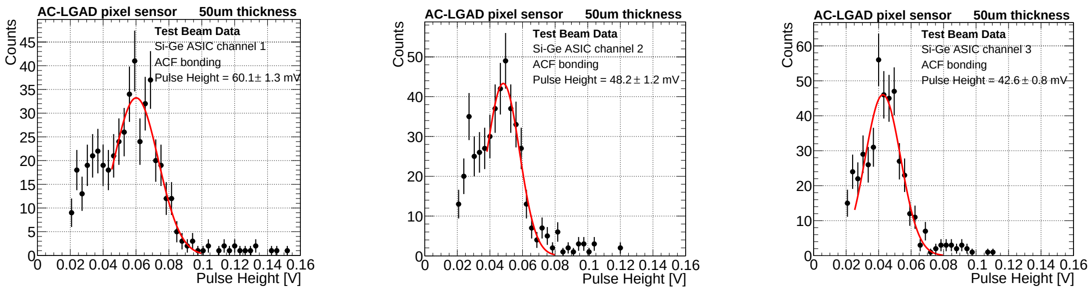
Figure 8: (a) Dependence of the pulse height on the IR laser power, (b) Dependence of the jitter on the pulse height. The AC-LGAD connected to the Si-Ge ASIC using wire bonding. The V_{DDA} is set to 1.5 V.

Table 1: Summary of the jitter and pulse height in IR laser measurement.

Sensor active thickness	50 μm	20 μm
Pulse height [mV]	70 mV	2.9 ps
Jitter [ps]	43 mV	4.5 ps

5.2 Measurement of the ACF bonded sample

The sensor used in this measurement is an E600-type AC-LGAD with a thickness of 50 µm, bonded to the Si-Ge ASIC using anisotropic conductive film (ACF) bonding. ACF bonding is a flip-chip interconnection technique that uses a thin adhesive film containing conductive particles, which conduct only in the vertical direction under heat and pressure. The pulse height distribution of the AC-LGADs was obtained by applying a position cut of 60 µm×60 µm on the 100 µm pitch electrode to eliminate crosstalk events. Figure 9 shows the pulse height distribution for each pixel. The pulse height of the Si-Ge ASIC channels 1, 2, and 3 are 60.1±1.3 mV, 48.2±1.2 mV, and 42.6±0.8 mV, respectively.



(a) Pulse height of the channel 1 **(b)** Pulse height of the channel 2 **(c)** Pulse height of the channel 3

Figure 9: The pulse height distribution of the ACF flip-chip bonded sample measured with a electron beam.

Table 2: Summary of the pulse height in testbeam measurement.

Channel number	1	2	3	1 at IR laser
Pulse height [mV]	60.1 ± 1.3 mV	48.2 ± 1.2 mV	42.6 ± 0.8 mV	70 mV

6. Conclusion

An AC-LGAD pixel sensor with a 100 µm electrode pitch has been developed in collaboration with HPK. The readout ASIC for the AC-LGAD is required to provide both low jitter and low power consumption. To meet these requirements, we investigated the potential of a Si-Ge BJT ASIC.

In the IR laser measurement, the lowest jitter was obtained at V_{DDA} = 1.5 V, which is approximately 3.6 times smaller than that of the discrete amplifier. The power consumption of the Si-Ge ASIC at this operating point is 144 µW per channel. Under MIP-equivalent conditions, the jitter of the Si-Ge ASIC was measured to be 2.9 ps when connected to the 50 µm-thick sensor and 4.5 ps when connected by wire bonding to the 20 µm-thick sensor. Furthermore, with the AC-LGAD bonded to the Si-Ge ASIC by ACF flip-chip bonding, the pulse heights of Si-Ge ASIC channels 1, 2, and 3 measured in a 3 GeV electron beam are 60.1±1.3 mV, 48.2±1.2 mV, and 42.6±0.8 mV, respectively.

In summary, the Si-Ge ASIC is capable of reading out the AC-LGAD with a jitter on the order of 1 ps. Moreover, the pulse height of the ACF flip-chip bonded sample under charged-particle injection is comparable to that measured with the IR laser.

Acknowledgments

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References

[1] ATLAS Collaboration, *Investigating the impact of 4D Tracking in ATLAS Beyond Run 4*, *ATL-PHYS-PUB-2023-023*.

[2] S. Kita, K. Nakamura, T. Ueda, I. Goya, and K. Hara, *Optimization of capacitively coupled Low Gain Avalanche Diode (AC-LGAD) sensors for precise time and spatial resolution* *Nucl. Instrum. Meth. A* **1048** (2023) 168009

[3] I. Dutta *et al.*, *Pixel and strip centimeter-scale AC-LGAD sensors*, *Nucl. Instrum. Meth. A* **1072** (2025) 170224.

[4] S. Kita, K. Nakamura, T. Imamura, I. Goya, and K. Hara, *Development of AC-LGAD detector with finer pitch electrodes for high energy physics experiments,* arXiv:2305.12355 [physics.ins-det] (2023).

[5] F. Martinelli, *SiGe Time Resolving Pixel Detectors for High Energy Physics and Medical Imaging*, EPFL PhD thesis, No. 9949, Lausanne (2022).

[6] S. Wada *et al.*, *Evaluation of characteristics of Hamamatsu low-gain avalanche detectors*, *Nucl. Instrum. Meth. A* **924** (2019) 380–386

[7] M. Milanesio *et al.*, *Time resolution of a SiGe BiCMOS monolithic silicon pixel detector without internal gain layer with a femtosecond laser*, *JINST* **19** (2024) P04029.

[8] J.V. Schmidt, J. Braach, D. Dannheim, R. De Oliveira, P. Svihra and M. Vicente Barreto Pinto, *Pixel detector hybridisation with anisotropic conductive films*, *JINST* **18** (2023) C01040.