



# KARAKTERIZACIJA SINGLE- PHOTON AVALANCHE DIODA (SPAD)

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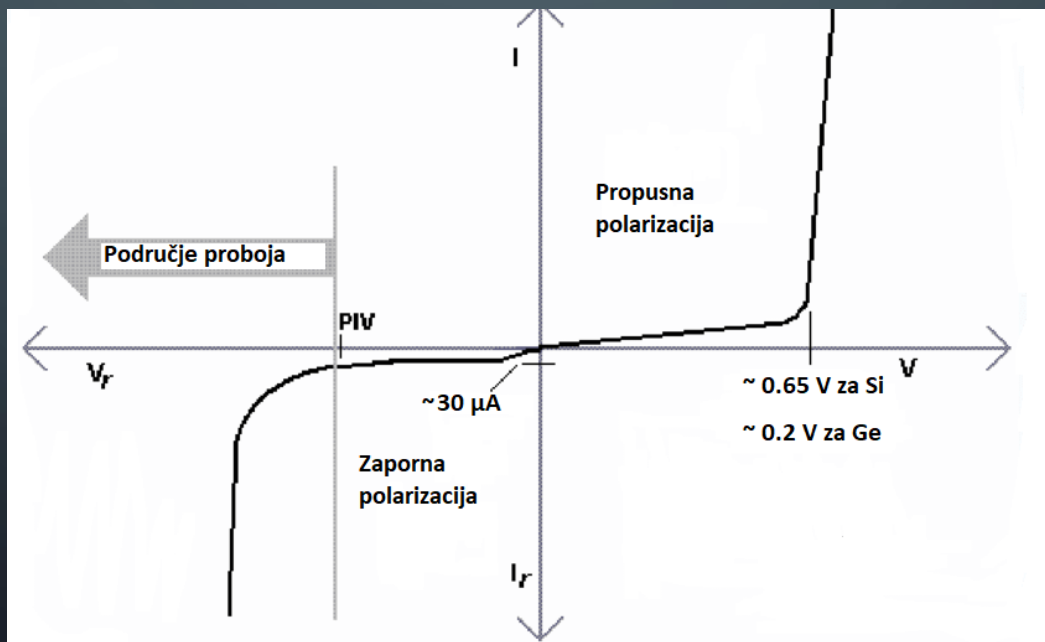
# SADRŽAJ

- Uvod
  - Diode – općenito
  - SPADs
- Eksperimentalni postav
- Mjerenja
  - Mjerenja šuma (engl. dark counts)
  - Mjerenja vremenske razlučivosti (engl. jitter)
  - Mjerenje ovisnosti efikasnosti o naponu
- Rezultati i zaključak
- Literatura

# DIODE

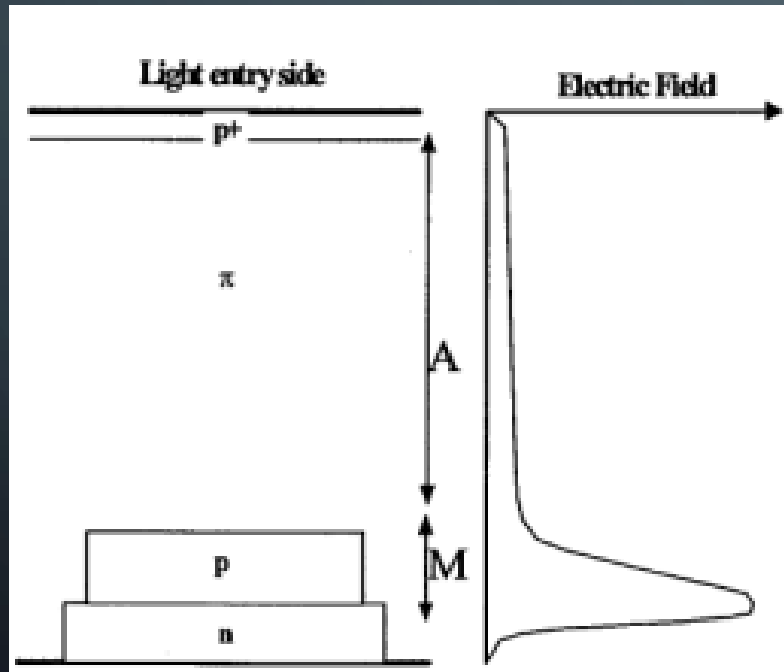


- pn-spoj
- Shockleyeva jednadžba:  $I_D = I_S(\exp(U_D/U_T)-1)$
- Pojava proboja: lavinski (engl. avalanche) i Zenerov
- I-V karakteristika:

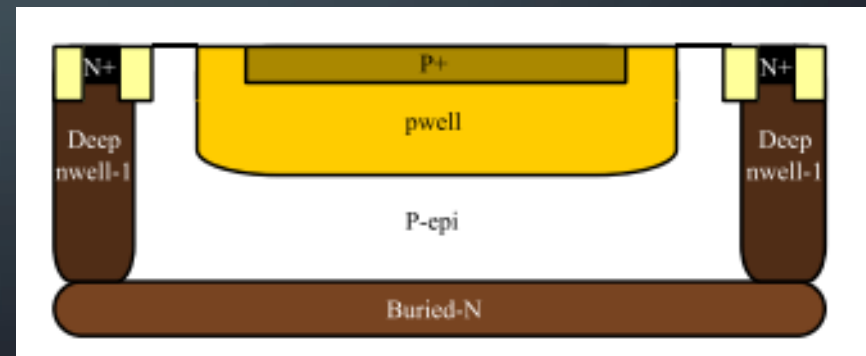


# SINGLE-PHOTON AVALANCHE DIODE (SPAD)

- Rad u Geigerovom modu (zaporna polarizacija, ispod graničnog napona)



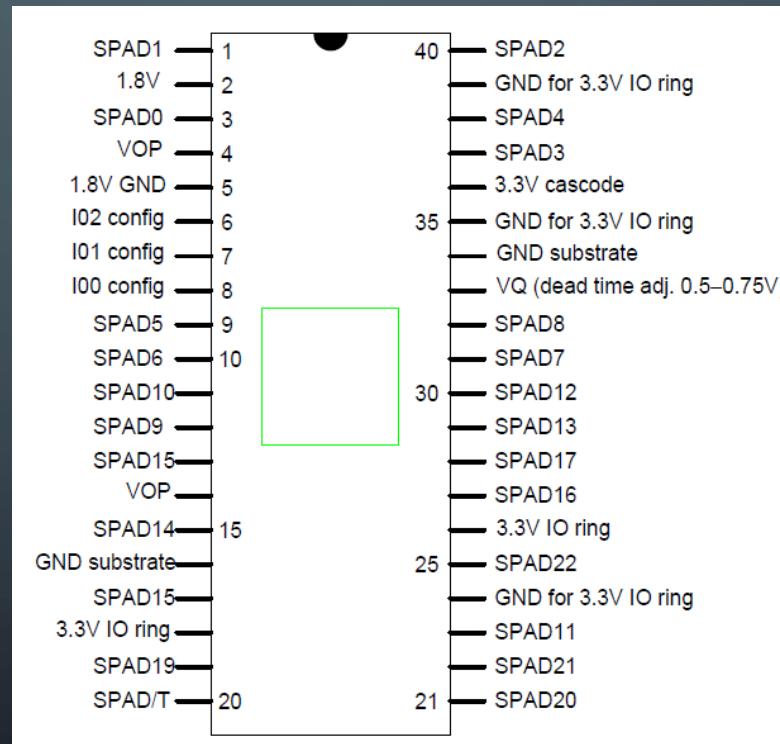
- Pasivno i aktivno gašenje lavine
- Koriste se u tomografiji, Time of flight kamerama, fluorescentnoj mikroskopiji te u kvantnoj optici kao dio generatora nasumičnih događaja



Chockalingam Veerappan, Edoardo Charbon, "A Low Dark Count p-i-n Diode Based SPAD in CMOS Technology", IEEE transactions on electron devices, vol. 63, no. 1, January 2016

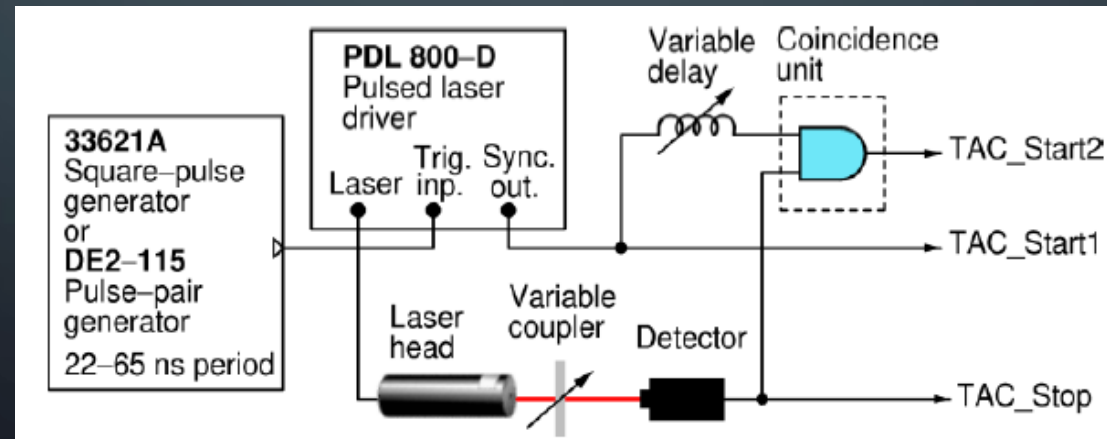
# EKSPERIMENTALNI POSTAV

- Mjerenja smo vršili na nasumično odabranim nanoSPAD diodama koje su se nalazile na nanoSPAD40-čipu:



# EKSPERIMENTALNI POSTAV

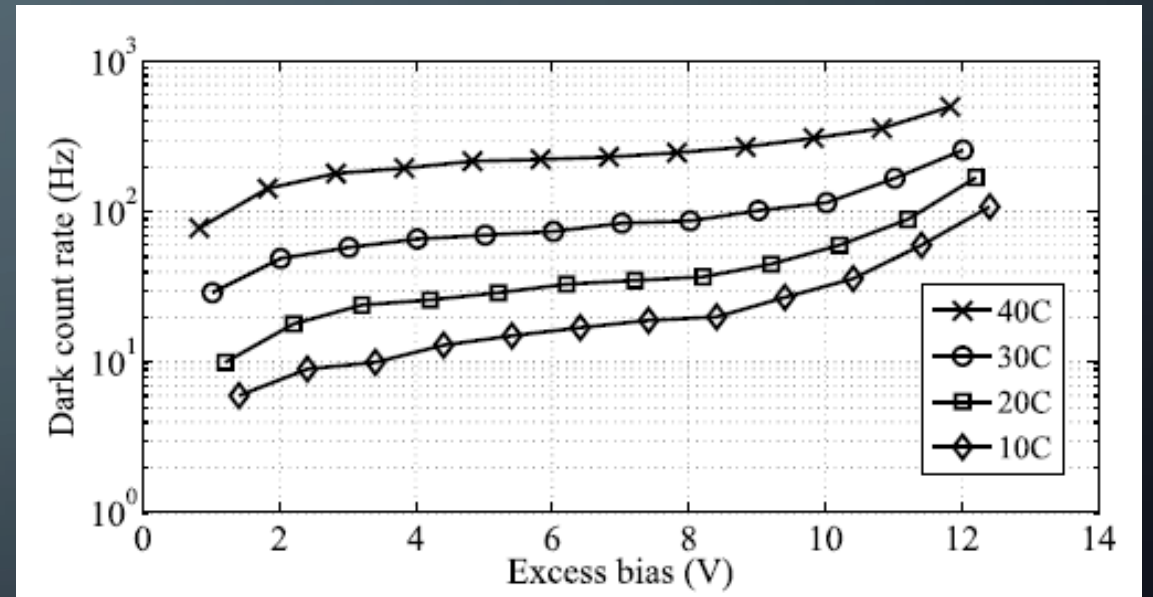
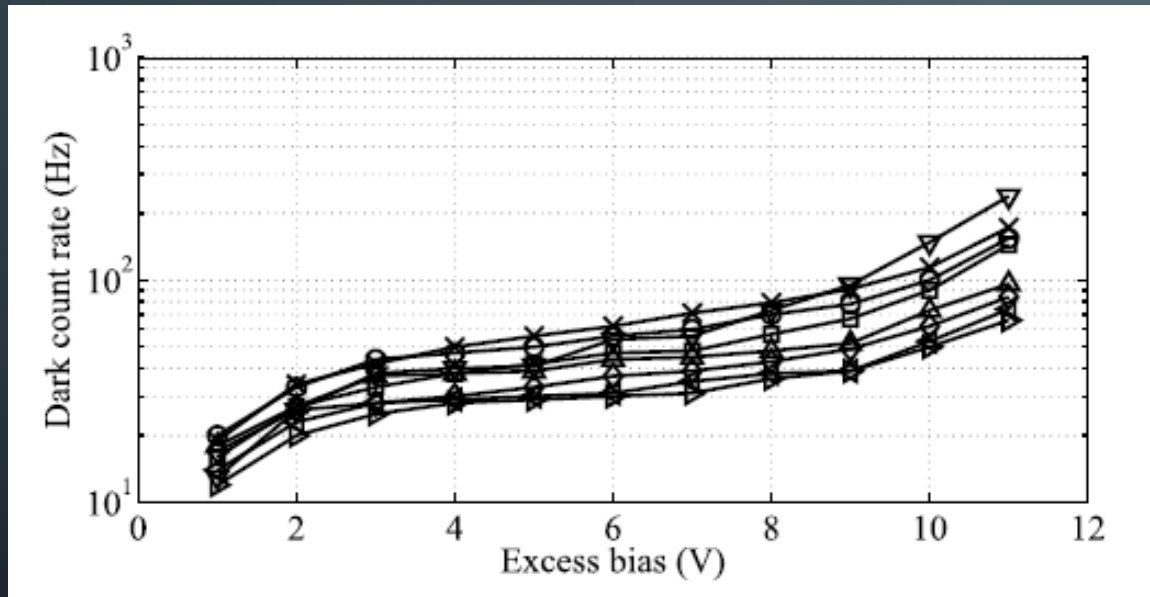
- Vremenska razlučivost:
  - Pikosekundni pulsni laser(PicoQuant) - driver(PDL 800-D) i laserska glava (LDH-P-670) => optički pulsevi FWHM-a širine 39 ps i valne duljine 676 nm
  - Za mjerenja vremenskih intervala između emisije i detekcije signala koristili smo dva digitalna ulaza (TAC Start1 i TAC Stop) ORTEC-ovog 567 Time-to-Amplitude Converter/Single-Channel Analyzer (TAC/SCA) modela.



Mario Stipčević, Bradley G. Christensen, Paul G. Kwiat and Daniel J. Gauthier, "Advanced active quenching circuit for ultrafast quantum cryptography", Opt. Express 25, 21861-21876 (2017)

# REZULTATI

- Mjerenje šuma
  - Uzrok: Termalna pobuđenja
  - Povećava se sa porastom napona iznad graničnog
  - Povećava se sa temperaturom
  - Ovisi o širini područja osiromašenja



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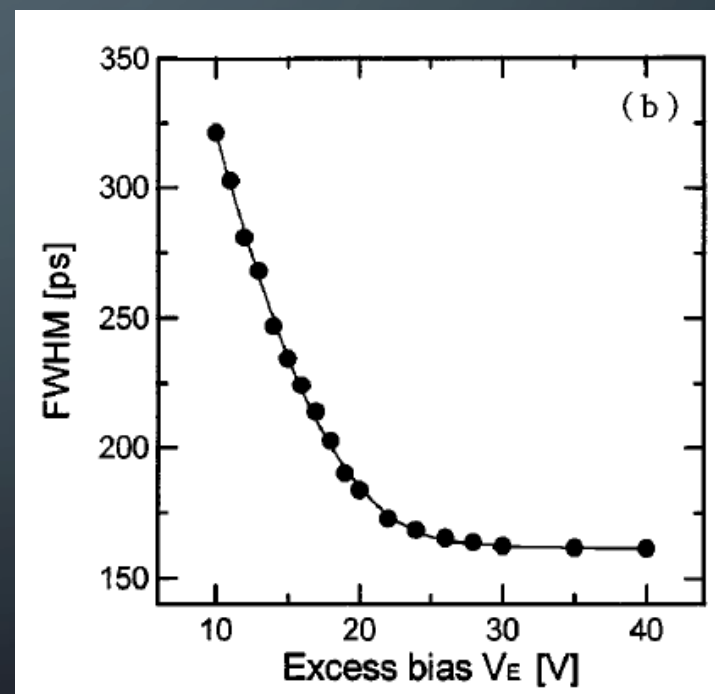
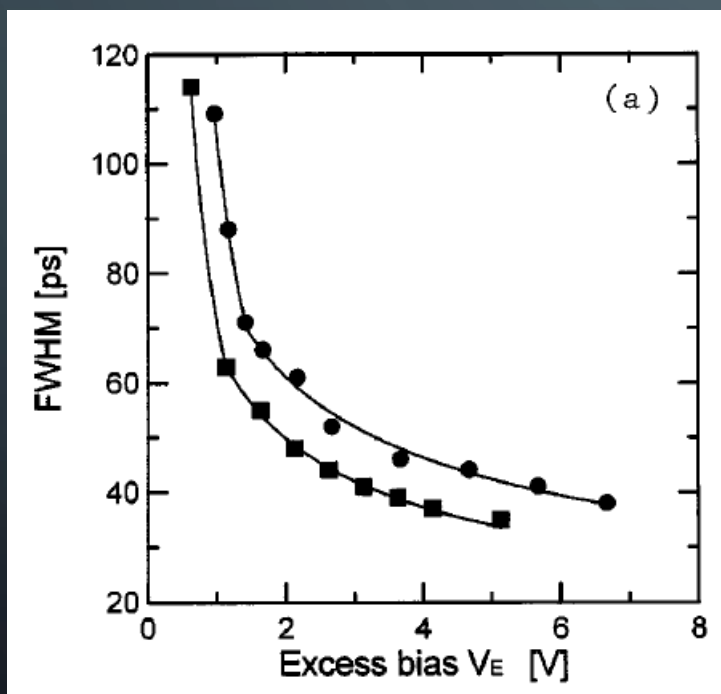
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  - Mjereno na sobnoj temperaturi, pri  $V_E = 27.2 \text{ V}$

SPAD	Šum (Hz)
SPAD 2	$43.4 \pm 0.6$
SPAD 4	$41.5 \pm 0.6$
SPAD 8	$39.6 \pm 0.6$
SPAD 7	$54.8 \pm 0.7$
SPAD 12	$42.6 \pm 0.6$
SPAD 13	$38.9 \pm 0.6$
SPAD 17	$61.7 \pm 0.7$
SPAD 16	$37.9 \pm 0.6$
SPAD 22	$46.5 \pm 0.6$

# REZULTATI

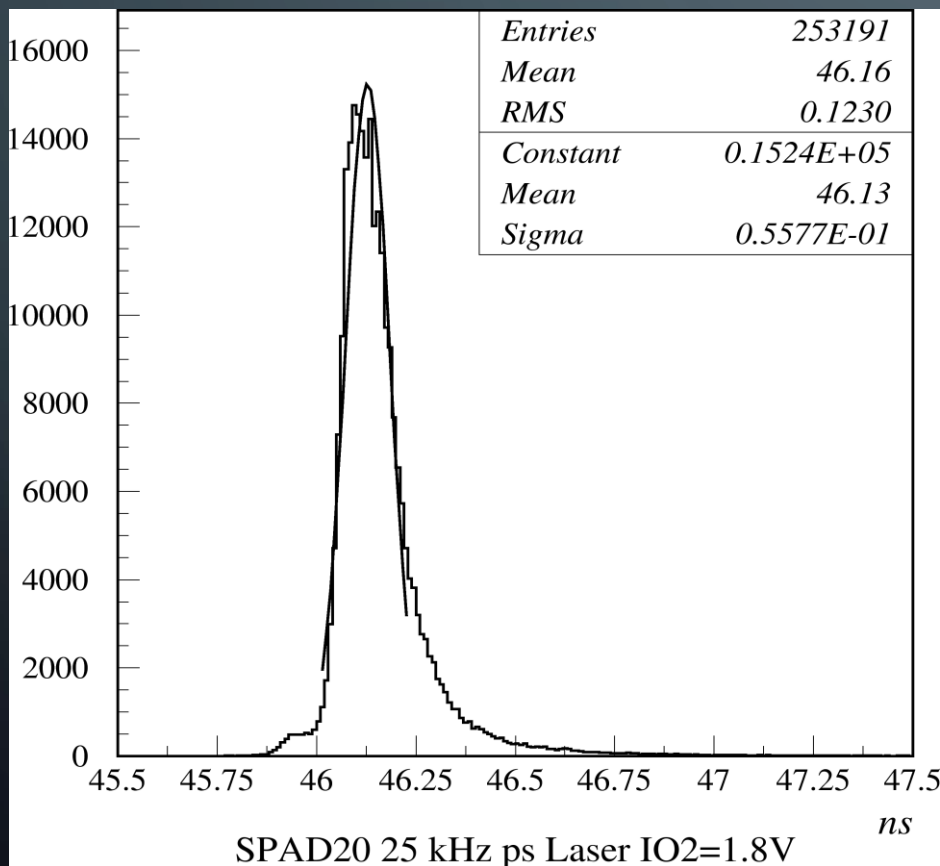
- Mjerenja vremenske razlučivosti
  - Vremenska razlučivost detekcije fotona ovisi o naponu  $V_E$ , temperaturi i debljini diode



S. Cova, M. Ghioni, A. Lacaita, C. Samori, and F. Zappa, "Avalanche photodiodes and quenching circuits for single-photon detection," Appl. Opt. 35, 1956-1976 (1996)

# REZULTATI

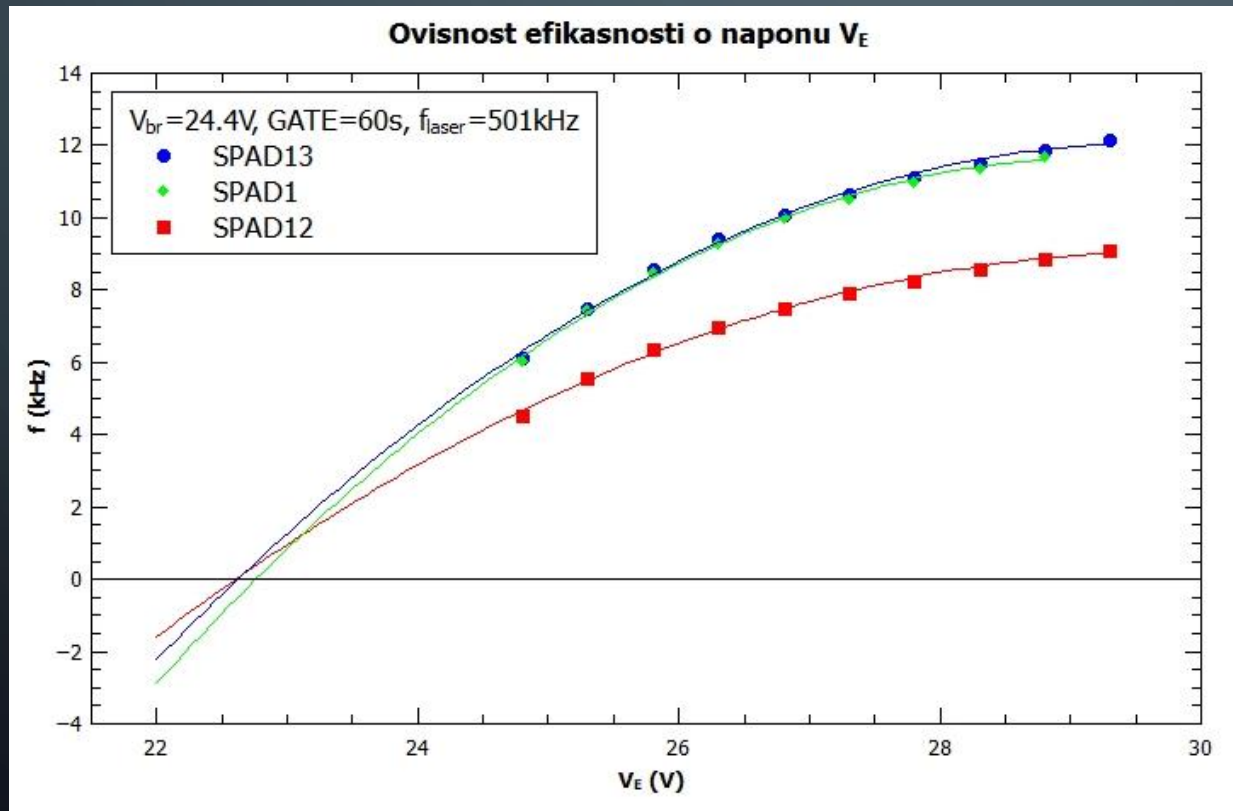
- Mjerenja vremenske razlučivosti



SPAD	FWHM (ps), V <sub>1</sub> = 800 mV	FWHM (ps), V <sub>2</sub> = 950 mV
SPAD 2	92.2	93.3
SPAD 4	100.9	95.9
SPAD 8	87.9	90.6
SPAD 7	88.2	93.7
SPAD 12	96.9	106.2
SPAD 13	90.2	101.4
SPAD 17	87.5	95.3
SPAD 16	91.5	106.7
SPAD 22	90.9	101.3

# REZULTATI

- Mjerenja ovisnosti efikasnosti o naponu



- Efektivni granični napon: 24.4 V
- Eksperimentalno dobiveni granični napon:  $(22.662 \pm 0.001)V$

# ZAKLJUČAK

- Opisane metode mogu se koristiti za karakterizaciju različitih vrsta SPAD-ova
- Dobiveni rezultati se mogu koristiti za izradu dioda sa boljom razlučivošću i manjim šumom
- Daljnja istraživanja:
  - Mjerenje ovisnosti šuma o temperaturi
  - Mjerenja ovisnosti efikasnosti o naponu za veći broj dioda bi dala još točniji iznos graničnog napona

# LITERATURA

- [1] Martin Pfennigbauer, Walter R. Leeb, Markus Aspelmeyer, Thomas Jennewein, Anton Zeilinger, "Free-Space Optical Quantum Key Distribution Using Intersatellite Links", CNES - Intersatellite Link Workshop, Nov. 27th and 28th 2003
- [2] Bernhard Wittmann, Sven Ramelow, Fabian Steinlechner, Nathan K. Langford, Nicolas Brunner, Howard M. Wiseman, Rupert Ursin and Anton Zeilinger, "Loophole-free Einstein-Podolsky-Rosen experiment via quantum steering", New J. Phys. 14, 053030 (2012)
- [3] Mario Stipčević, Bradley G. Christensen, Paul G. Kwiat and Daniel J. Gauthier, "Advanced active quenching circuit for ultrafast quantum cryptography", Opt. Express 25, 21861-21876 (2017)
- [4] S. Cova, M. Ghioni, A. Lacaita, C. Samori, and F. Zappa, "Avalanche photodiodes and quenching circuits for single-photon detection," Appl. Opt. 35, 1956-1976 (1996)
- [5] Chockalingam Veerappan, Edoardo Charbon, "A Low Dark Count p-i-n Diode Based SPAD in CMOS Technology", IEEE transactions on electron devices, vol. 63, no. 1, January 2016
- [6] Mario Stipčević, "Quantum random flip-flop and its applications in random frequency synthesis and true random number generation", Review of scientific instruments 87, 035113 (2016)
- [7] Željko Butković, Julijana Divković Pukšec, "Elektronika 1, I dio", Fakultet elektrotehnike i računarstva, Zagreb 2006.

The image features a dark blue gradient background with white, stylized circuit board traces in the corners. These traces consist of straight lines and small circles, resembling electronic components or connections. The traces are located in the top-left, top-right, bottom-left, and bottom-right corners, framing the central text.

**HVALA NA PAŽNJI!**