

TinyTapeout: A Shared Silicon Tapeout Platform Accessible To Everyone

Matt Venn
 TinyTapeout, YosysHQ
 Email: matt@tinytapeout.com

Index Terms—ASIC, Multi Project Chip, Open Source Silicon, TinyTapeout.

I. INTRODUCTION

TINYTAPEOUT is a multi project chip platform that makes it easier and cheaper than ever to get ASIC designs manufactured.

Open source tools and process design kit (PDK [1]) are used, so no licenses or NDAs are needed. As the tools are run in the cloud, no software needs to be installed on the user's machine. However, as long as the template structure is followed, proprietary tools can be used.

Around 400 open source designs are multiplexed to 24 general purpose input/output (GPIO) pins, and after manufacture the chips are mounted to a demonstration board for easy testing. Each chip contains every design, which can be activated and tested in turn.

Additionally, each participant submits documentation for their design, collected to form a printable datasheet [2] along with an online index at TinyTapeout.com/runs/ [3]. The datasheet helps participants to explore each other's design in addition to their own.

By separating the cost of area and the physical chip, a group can share the cost of chip packaging and PCBs, while still getting to test and measure all the designs on the chip. In a classroom setting this helps to reduce the overall price, as students can share a smaller number of PCBs while each submitting their own design.

Each tile (Fig. 1) is approximately $160 \times 100 \mu\text{m}^2$, enough for around 1000 logic gates on the Skywater 130nm open source PDK. Tiles can be joined to enable larger designs. Analog and mixed signal support is being added for the next shuttle.

Community engagement has been strong with 756 designs submitted over the first 5 shuttles. Some highlights are listed in section IX. The online chat server has 1000 members with 1600 subscribed to the mailing list. Submitters tend to identify as hobbyists, students and teachers as shown in Fig. 2.

The first [4] free and experimental shuttle with 152 designs was submitted to the seventh Google sponsored [5] lottery multi project wafer (MPW) shuttle in September 2022. The next 4 shuttles combined 582 designs and were sponsored by and manufactured with the Efabless [6] chipIgnite MPW service. Table I shows a summary of all the shuttle runs to date.

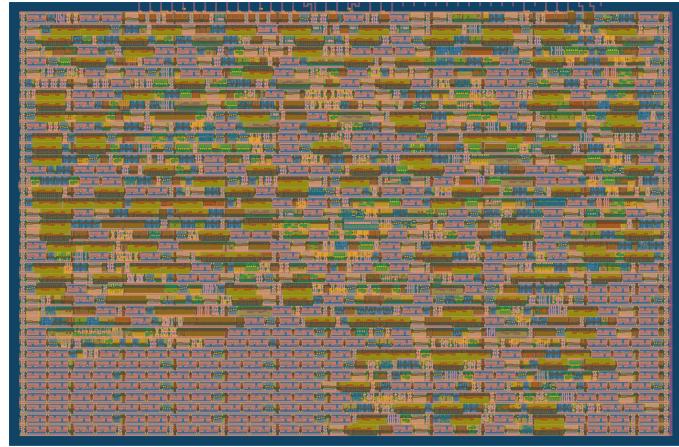


Fig. 1. 2D render of a single tile

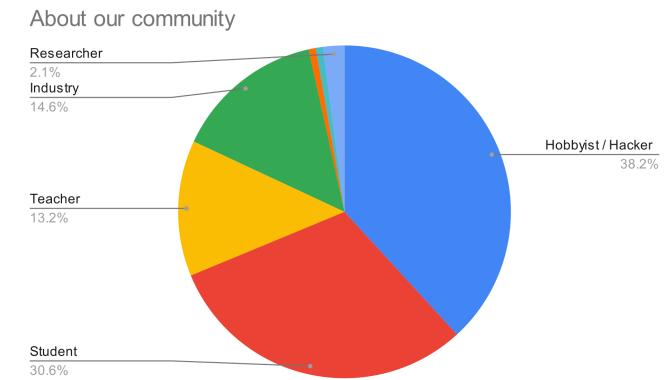


Fig. 2. How TT04 submitters identified themselves.

The rest of this paper will discuss the TinyTapeout design flow, multiplexer evolution, circuit boards, silicon results and next steps.

II. DESIGN FLOW

Design entry is done mostly with Verilog or Wokwi [7]. Wokwi is a web based schematic based editor that is an easy way to get started for people with no prior hardware description language (HDL) experience. The TinyTapeout website [8] includes a basic getting started guide for drawing circuits available in English and Spanish.

The design flow consists of templating a GitHub [9] repository, adding a design, waiting for the tests and binary layout

TABLE I
STATISTICS FOR EACH OF THE TINYTAPEOUT SHUTTLE RUNS

Run	Launched	Shuttle	Designs	Estimated delivery date	Architecture
TT01	2022-08-17	MPW7	152	n/a	Scan chain
TT02	2022-11-09	2211Q	165	2024-01-30	Scan chain
TT03	2023-03-01	2304C	249	2024-02-28	Scan chain inverted clock
TT04	2023-07-01	2309	143	2024-04-15	Mux
TT05	2023-09-11	2311	174	2024-05-12	Split Mux
TT06	2024-02-01	2404	TBD	2024-11-30	Split Mux

Routing stats

Utilisation (%)	Wire length (um)
51.7	16572

Cell usage by Category

Category	Cells	Count
Fill	decap fill	1145
Combo	a21ai nand3b a221o o31a or2b a21o a21bo nor2b o31ai a41o a21oi a211o o21bs a21a o21bai a2bb2o o3b o221a a31o a22o o32a o22a a32o a2111o and2b and3b or4b or4bb o211a a2111o c2bb2a a211oi and4bb o211a a22oi a31oi o311a	249
Tap	laptopvrgnd	246
Flip Flops	dfftp	146
Buffer	buf clkbuf	127
AND	and2 a21boi and3 and4	97
Mux	dlygate4x3 dlymetal6x2s comb	84
OR	or2 xor2 or2x4	81
NOR	xnor2 nor2 nor3 nor4	64
NAND	nand2 nand3 nand4 nand2b	52
Inverter	inv	37
Multiplexer	mu2 mux4	9
Diode	diode	1

947 total cells (excluding fill and tap cells)

Fig. 3. The summary table of the GDS job.

files (GDS [10]) generation to complete, then submitting to a quarterly shuttle.

The GitHub templates [11] make use of GitHub Actions [12]—an automatic continuous integration system that is triggered every time the repository is updated.

There are 4 main jobs:

- 1) GDS: installs OpenLane [13] and the Sky130 [14] PDK, builds the GDS and generates a summary of the design (Fig. 3). The summary includes utilization, standard cells used, a 2D render (Fig. 1) and an interactive 3D viewer (Fig. 4). This job can also optionally run a gate-level verification.
- 2) Verification: installs the YosysHQ open source CAD suite which includes many common electronic design automation (EDA) tools. Then iVerilog [15] and cocotb [16] are used to run any testbenches included.
- 3) Documentation: generates a preview of the documentation.
- 4) Precheck: a number of tests are run to make sure that the design doesn't cause design rule check (DRC) errors after integration into the chip.

Successful GDS, Documentation, and Precheck jobs are required to submit to a shuttle. Verification is optional but highly encouraged. Wokwi designs can make use of an integrated truth table testing system [17].

While the process can be done entirely in the browser, it's also possible to install a local copy of the tools [18], which can help to reduce iteration time, especially for tests and verification.



Fig. 4. The interactive 3D viewer.

III. SCAN CHAIN ARCHITECTURE

TinyTapeout started as an experiment in fitting as many designs as possible into the 10 mm² available on the Google lottery shuttles (Fig. 5). As a fast proof of concept, a scan chain was chosen. Each design had 8 inputs and 8 outputs. Clock and reset were optional and not treated specially. The chain was formed of scan flops [14], a type of flip flop with an integrated multiplexer at its input. An example showing a two-design scan chain is shown in Fig. 6.

Each design sends data into the scan flops secondary input and receives input from the output of the flop via a latch. The chain is built [19] by sending data from the output of the previous scan flop into the next scan flop's primary input.

This arrangement allows the loading of data into any of the designs, and then capturing the output and clocking that through the rest of the chain to the output.

While relatively easy to implement, the downside is the latency. The more designs in the chain, the longer it takes to send and receive data. For example, assuming a 50 MHz scan chain clock, 250 designs with 8 inputs and 8 outputs, the maximum refresh rate is $50\text{ MHz}/(8 \times 250) = 25\text{ kHz}$.

TT01's scan chain was embedded into each design, which meant that a user could unintentionally remove it, breaking the chain. This risk was mitigated with a formal [20] equivalence check—proving the chain was present in the submitted design. For TT02 and TT03, the scan chain was separated into a separate macro block that the user can't modify.

Another concern was hold violations due to the large number of serially connected flops and potentially large clock skews due to long signal wires. This was mitigated by reclocking the output data with a negedge flop, providing substantially more hold margin.

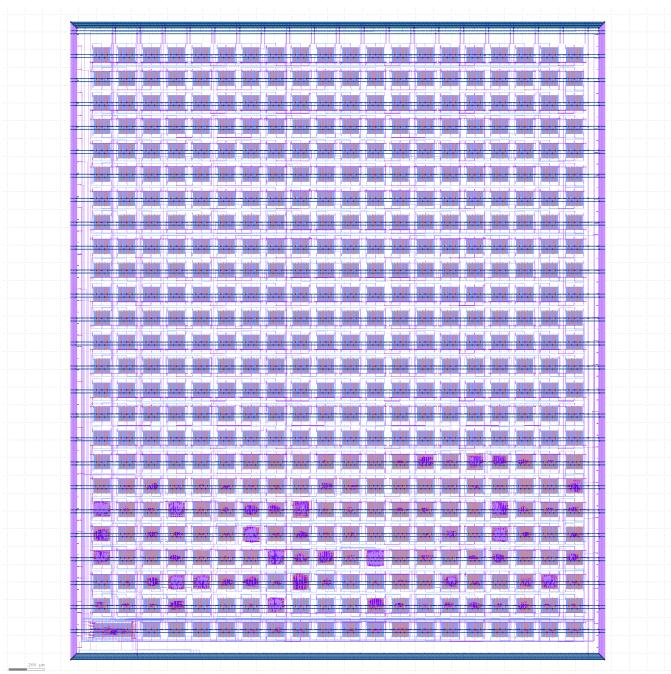


Fig. 5. 500 designs connected in a chain for TT01, with the scan chain driver in the lower left corner.

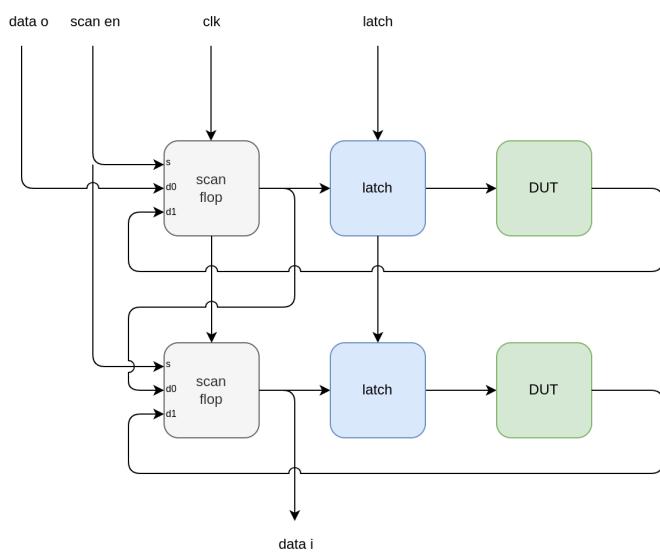


Fig. 6. A simplified view of 2 designs in the chain.

After static timing analysis (STA) it was discovered that the clock duty cycle could change substantially due to the 500 sequential clock drivers. Depending on the clock buffers and capacitance between each design, the clock duty cycle could either increase or decrease, with this effect accumulated over the chain.

For TT01 and TT02 each design used two clock buffers, with the internal flops driven after the first buffer. TT03 used inverting clock buffers, with only one between the clock in and out. Fig. 8 shows a comparison between the TT02 and TT03 clock buffer designs. By inverting the clock between each design, any asymmetry in the clock pulse is evenly spread

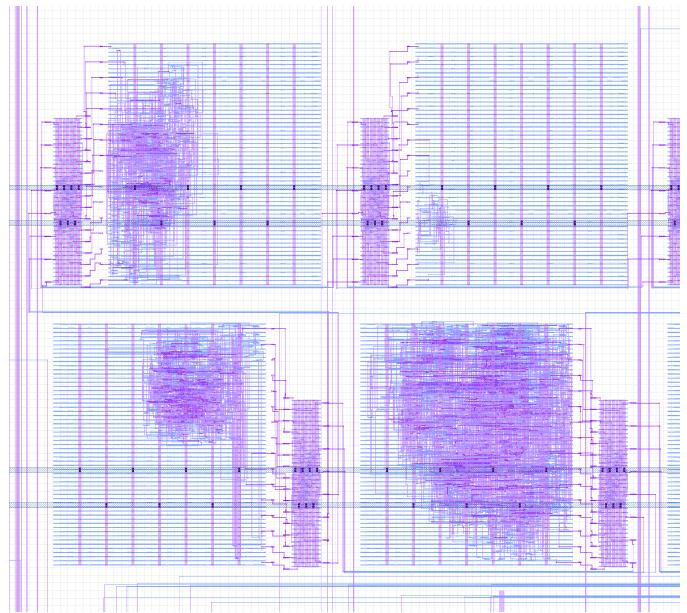
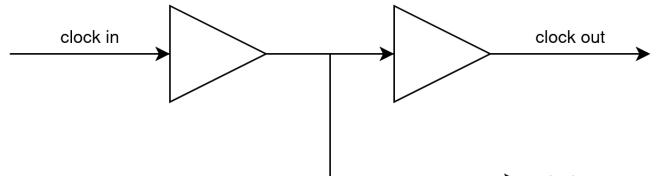


Fig. 7. TT02 designs with separate scan chain blocks.

TT02



TT03

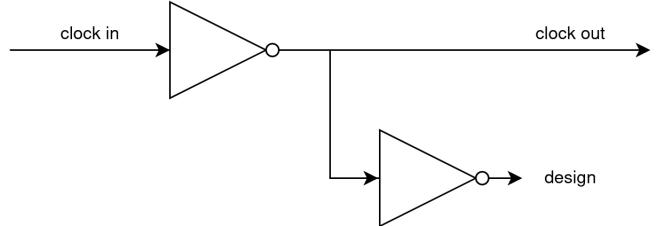


Fig. 8. TT03 buffers the output from the clock network into each design. Clock polarity is alternated between designs to minimize asymmetry between positive and negative cycles.

across the negative and positive cycles.

The verification effort [21] was broad and included a community review, register transfer level (RTL) and gate level (GL) simulation, Formal Verification [22], STA, layout vs schematic (LVS), DRC, and device level static verification [23].

IV. CIRCUIT BOARDS

After manufacture, the chips are mounted onto small carrier boards with 0.1 inch headers. This allows people with limited surface mount technology (SMT) assembly experience to build their own demonstration boards.

The carrier fits onto the demonstration board shown in Fig. 9. The demonstration boards are designed primarily for

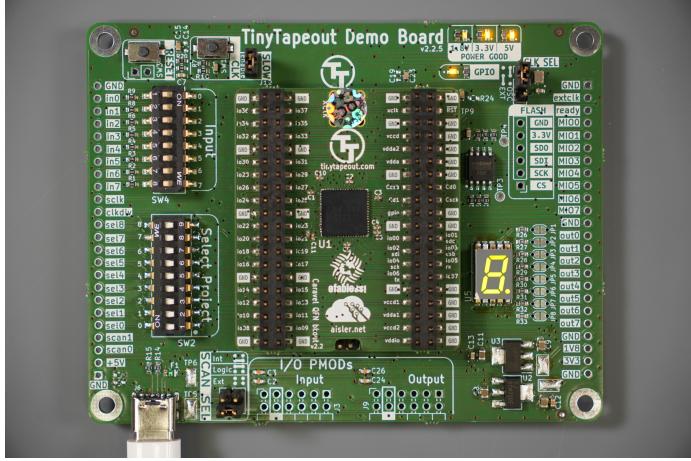


Fig. 9. The demonstration board. Certified Open Source Hardware ES000040 [24].

ease of use by beginners, with enough flexibility for power users. As all signals are below 50 MHz, no special layout was needed.

The demonstration board provides:

- USB-C for power connection,
- 1.8 V and 3.3 V power supplies for core and IO,
- 20 MHz oscillator,
- Buttons for reset and single-step clock,
- An 8-way DIP switch for inputs,
- A 9-way DIP switch for design selection,
- A 7-segment LED display for the outputs,
- Headers for all IO, including 2 standard Digilent ports (PMOD),
- A header to select the internal clock or provide one externally,
- A header to select internal or external scan chain driver,
- A header to engage an automatic clock divider in input pin 0.

V. SCAN CHAIN SILICON RESULTS

TT02 chips were received in October 2023, 11 months after the chips were submitted for manufacture on Efabless chipIgnite 2211Q. The chips were tested for the first time in public on a livestream [25]. The chain was validated, and a few of the designs were shown to be working.

In the following days another 30 designs were tested and shown to be working.

After measuring the clock asymmetry (Fig. 10) and maximum frequency it was decided to run the production boards with a 20 MHz oscillator, resulting in a 10 MHz scan chain.

Some designs didn't function as expected, which in most cases was due to faults in the submitted design.

As well as 82 Verilog designs, 64 used the Wokwi graphical editor, 6 used alternative HDLs like VHDL, Amaranth [26] and Chisel [27]. Some Wokwi designs using combinational logic in clock paths (Fig. 11) worked in simulation but failed in hardware. This was due to the lack of timing data in the simulation, and wasn't detected by STA because the clock

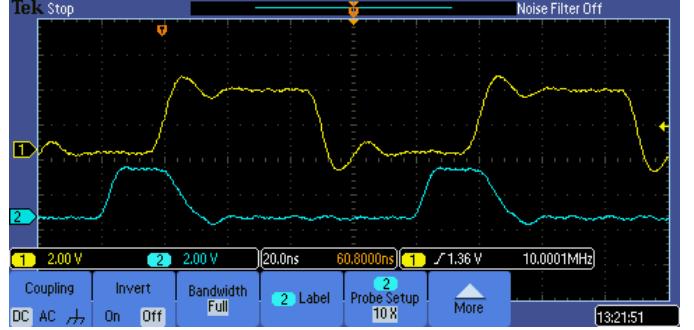


Fig. 10. Measurement from TT02 silicon, with input clock in yellow and the distorted output clock in blue.

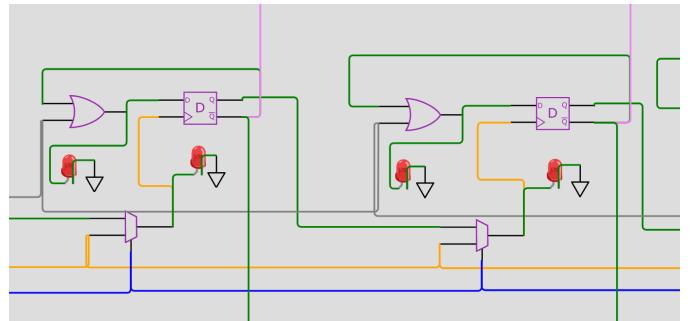


Fig. 11. Combinational logic in the clock path of one of the failed designs.

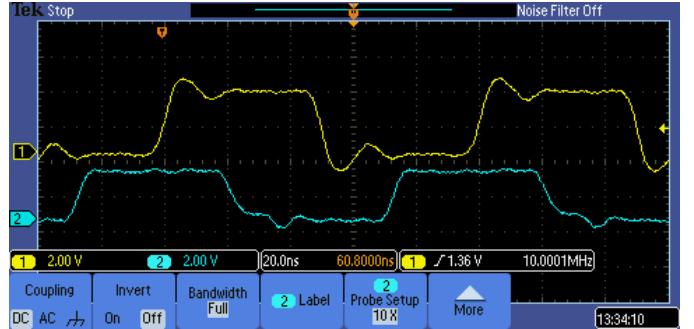


Fig. 12. Measurement from TT03 silicon.

paths were not known. A detailed analysis has yet to be carried out.

At the time of writing, PCBs are in production and are expected to ship to customers by the end of January 2024.

TinyTapeout 3 silicon was received in January 2024, and the updated scan chain shows a more symmetric (Fig. 12) output clock at the end of the chain. This will allow a faster scan chain clock, resulting in a faster update frequency.

VI. BEYOND THE SCAN CHAIN

The biggest limitation of the scan chain based architecture was the IO bandwidth and latency. A new architecture was needed for TinyTapeout 4, so proposals were gathered from the community. An online video call was held and the 10 proposals discussed. The winning design was a fairly straightforward multiplexer design shown in Fig. 13.

The physical layout (shown in Fig. 14) consists of a central controller connected up and down to two vertical spines.

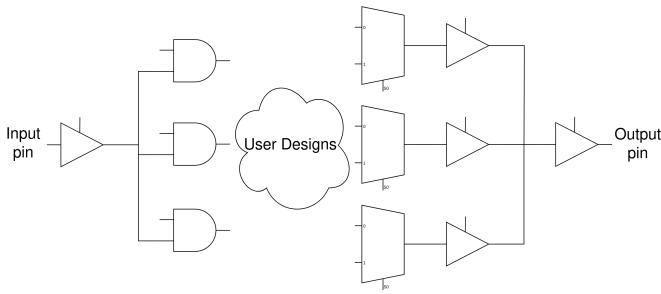


Fig. 13. Simplified diagram of the multiplexer architecture.

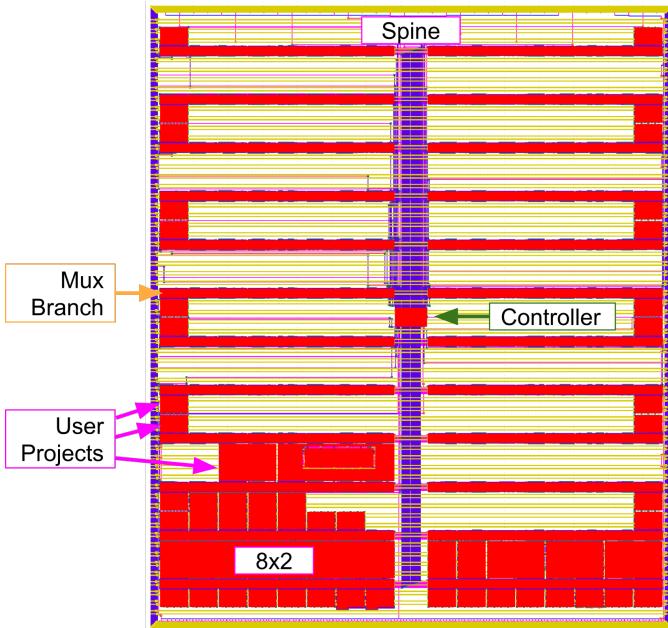


Fig. 14. The TT03.5 test design.

TABLE II
COMPARISON BETWEEN TT03 AND TT04

Parameters	TT03	TT04
Max clock speed	12.5 kHz	50 MHz
Max design size	$150 \times 170 \mu\text{m}^2$	$1359 \times 225 \mu\text{m}^2$
Input pins	8	10
Output pins	8	8
Bidirectional I/O pins	None	8
Custom GDS file	X	✓

Twenty-four horizontal muxes connect to the spine with each supporting 16 designs. This allows up to 384 separate single tile designs. Multiple tile designs were also enabled, allowing a maximum project size of 8×2 tiles or $1359 \times 225 \mu\text{m}^2$ —around 20 000 logic cells. Table II shows the key differences between TT03 and TT04.

Another major limitation of TT01 to TT03 was the small number of IO. The scan controller used 9 GPIOs to select the currently active design, which, while simplifying the demo board, wasted valuable pins. With TT04, the parallel design selection was dropped in favor of a serial protocol. The extra pins were then used as bidirectional pins, giving each design clock, reset, and 24 IO.

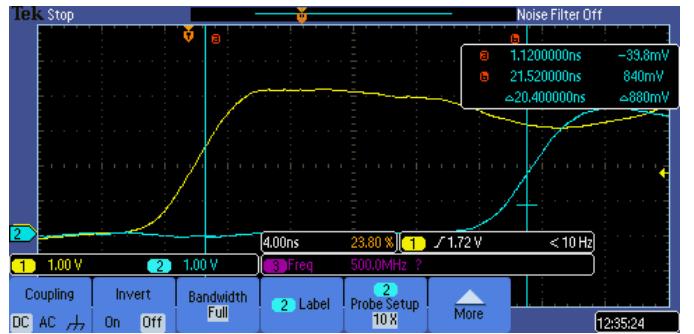


Fig. 15. Round trip latency on a rising edge of about 20 ns.

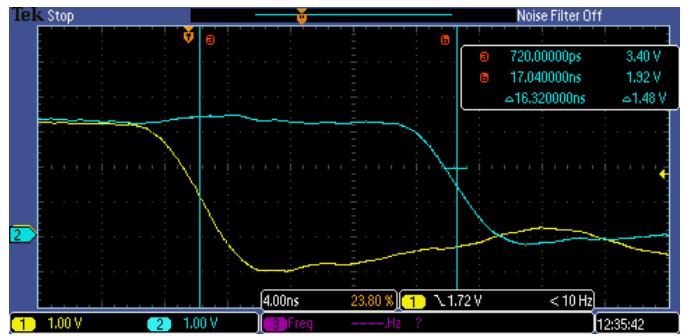


Fig. 16. Round trip latency on a falling edge of about 16 ns.



Fig. 17. VGA clock design running on TT03.5 silicon.

An invite-only experimental shuttle [28] was submitted with 32 designs to Efabless chipIgnite 2306C. Two of the designs included a power gate as a stepping stone to supporting analog and mixed-signal designs.

VII. MULTIPLEXER SILICON RESULTS

After silicon was received, the worst round trip latency was measured to be 20 ns as shown in Fig 15 and 16. Some designs have been validated, including a VGA clock project (Fig. 17) that takes advantage of the new higher speed IO.

The new chip pinout and serial design selection required a new demonstration board (Fig. 19) that included an easy way

```
enabling design tt_um_test by sending 102 [0b01100110] pulses
design repo https://github.com/TinyTapeout/tt03p5-test @ 434c5d508d20053bea346881a61355f87ea1ca91
0 0 0 0
1 0 0 0
0 1 0 0
1 1 0 0
0 0 1 0
1 0 1 0
0 1 1 0
1 1 1 0
0 0 0 1
```

Fig. 18. A MicroPython program [30] enabling a design, clocking it, and printing the results.

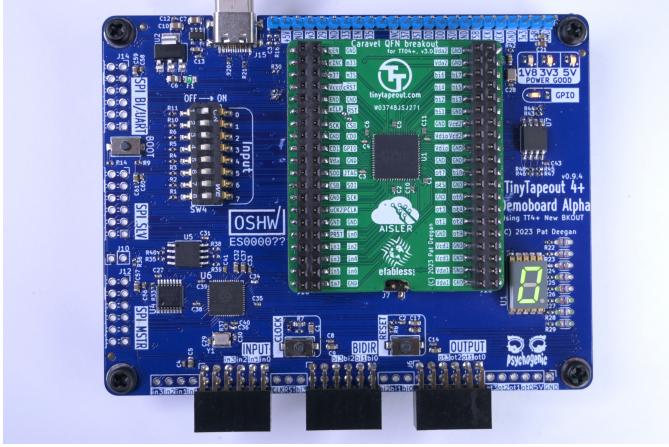


Fig. 19. The TT04+ demo board [31].

to select the design. The RP2040 microcontroller was chosen as a co-processor as it allows:

- Drag and drop firmware updates on any OS,
- Runs MicroPython [29], ideal for beginners to enable and test their designs (Fig. 18),
- External memory emulation via PIO and DMA.

An additional PMOD expansion port was added for the bidirectional pins, and the community has started to standardize on pinouts [32] making it easier to test each other's designs. A new repository was created to house user-contributed PMODs [33], for example the VGA PMOD shown in Fig. 20.

An additional set of 3 PMOD expansion ports were added that mixed input and outputs, allowing the most common standard PMODs to be used. For more information about the circuit board, pinout and PMOD support see the repository [31].

VIII. IMPROVING THE MULTIPLEXER AND MIXED SIGNAL SUPPORT

TT05 split the mux into two parts to improve performance. As each spine segment is now half as long, it will have half the capacitance. We expect to reduce the round trip latency to around 10 ns.

For TT06, the Caravel harness will be replaced by OpenFrame [34], an alternative harness provided by Efabless that uses the same padding but removes the RISC-V coprocessor. This results in 5 mm² more space for user designs, and 12 more pins that will be used for analog signals.

For increased safety, all designs will be power-gated, which allows designers to take more risks or use custom flows.

Analog and mixed-signal designs will be enabled by adding an analog multiplexer based on transmission gates [35]. This

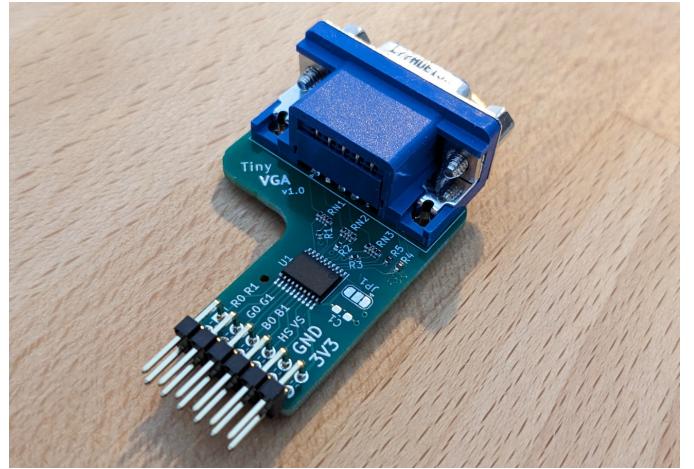


Fig. 20. A user-contributed VGA output PMOD.

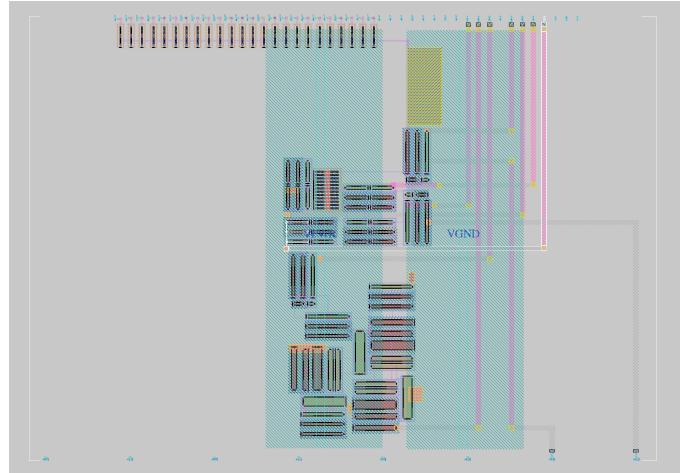


Fig. 21. Ring oscillator and DAC design submitted to TT05 with a transmission gate highlighted (auto-placed and auto-routed using an experimental analog P&R tool).

allows up to 192 designs to share the analog pins between them. The transmission gates were tested as part of an experimental analog submission to TT05 shown in Fig. 21.

TT06 is planned to open for digital designs at the end of January 2024, for analog designs at the end of February, and to close on April 19th, 2024.

IX. SILICON SHOWCASE

A small sample of the types of designs possible with TinyTapeout are listed below:

- Serial FPGA (Link)
- Synthesizable Digital Temperature Sensor (Link)
- 395 standard cells with mux (Link)
- FM transmitter with I2S input (Link)
- USB full speed - (Link)
- A Linux capable RISC-V CPU - (Link)

An index of all submitted designs can be found at TinyTapeout.com/runs/ [3].

X. ACKNOWLEDGEMENTS

- 1) Uri Shaked for Wokwi development and lots more.
- 2) Sylvain Munaut for help with scan chain improvements and multiplexer design.
- 3) Mike Thompson and Mitch Bailey for verification expertise.
- 4) Jix for formal verification support.
- 5) Proppy for help with GitHub actions.
- 6) Maximo Balestrini for the amazing renders and the interactive GDS viewer.
- 7) Harald Pretl for advice and analog support.
- 8) The team at YosysHQ and all the other open source EDA tool makers.
- 9) Efabless for running the shuttles and providing OpenLane and sponsorship.
- 10) Tim Ansell and Google for supporting the open source silicon movement.
- 11) Pat Deegan for PCB development.
- 12) The TinyTapeout community for all their contributions.
- 13) The Zero to ASIC course community for all their support.

REFERENCES

- [1] M. Venn, “PDK,” <https://www.zerotoasiccourse.com/terminology/pdk/>, (accessed March 6, 2024).
- [2] ——, “Datasheet PDF - TinyTapeout Repository,” <https://github.com/TinyTapeout/tinytapeout-02/raw/tt02/datasheet.pdf>, (accessed March 6, 2024).
- [3] ——, “TinyTapeout Runs,” <https://tinytapeout.com/runs/>, (accessed March 6, 2024).
- [4] ——, “First Shuttle - TinyTapeout Runs,” <https://tinytapeout.com/runs/tt01/>, (accessed March 6, 2024).
- [5] E. Mahintorabi, “Announcing the GlobalFoundries Open MPW Shuttle Program - Google Open Source Blog,” <https://opensource.googleblog.com/2022/10/announcing-globalfoundries-open-mpw-shuttle-program.html>, (accessed March 6, 2024).
- [6] Efabless, “Efabless,” <https://efabless.com/>, (accessed March 6, 2024).
- [7] U. Shaked, “Wokwi,” <https://wokwi.com/>, (accessed March 6, 2024).
- [8] M. Venn, “TinyTapeout,” <https://tinytapeout.com/>, (accessed March 6, 2024).
- [9] GitHub, “GitHub,” <https://github.com/>, (accessed March 6, 2024).
- [10] M. Venn, “GDS2 File Format - Zero to ASIC Course,” <https://www.zerotoasiccourse.com/terminology/gds2/>, (accessed March 6, 2024).
- [11] U. Shaked, “Verilog Template - TinyTapeout Repository,” <https://github.com/TinyTapeout/tt06-verilog-template>, (accessed March 6, 2024).
- [12] GitHub, “GitHub Actions Documentation,” <https://docs.github.com/en/actions>, (accessed March 6, 2024).
- [13] Efabless, “OpenLane documentation,” <https://openlane.readthedocs.io/en/latest/>, (accessed March 6, 2024).
- [14] S. P. Authors, “Skywater PDK Documentation,” https://skywater-pdk.readthedocs.io/en/main/contents/libraries/sky130_fd_sc_hdll/cells/sdfxrt/README.html, (accessed March 6, 2024).
- [15] S. Williams, “iVerilog,” <https://github.com/steveicarus/iverilog/>, (accessed March 6, 2024).
- [16] F. Foundation, “cocotb,” <https://www.cocotb.org/>, (accessed March 6, 2024).
- [17] P. Deegan, “Wokwi Automated Testing - TinyTapeout,” https://tinytapeout.com/digital_design/wokwi_automated_testing/, (accessed March 6, 2024).
- [18] U. Shaked, “Locally installing the tools,” <https://docs.google.com/document/d/1aUUZ1jthRpg4QURIIyzlOaPWlmQzr-jBn3wZipVUPt4>, (accessed March 6, 2024).
- [19] M. Venn, “Updating Inputs and Outputs of a Design - TinyTapeout Repository,” <https://github.com/TinyTapeout/tinytapeout-02/blob/tt02/INFO.md#updating-inputs-and-outputs-of-a-specified-design>, (accessed March 6, 2024).
- [20] J. Harder, “TinyTapeout Scan - GitHub Repository,” https://github.com/jix/tinytapeout_scan, (accessed March 6, 2024).
- [21] M. Venn, “Verification Documentation - TinyTapeout Repository,” <https://github.com/TinyTapeout/tinytapeout-02/blob/tt02/VERIFICATION.md>, (accessed March 6, 2024).
- [22] YosysHQ, “SymbiYosys (SBY) - YosysHQ Repository,” <https://github.com/YosysHQ/sby>, (accessed March 6, 2024).
- [23] M. Bailey, “CVC - Verification Documentation - TinyTapeout Repository,” <https://github.com/TinyTapeout/tinytapeout-02/blob/tt02/VERIFICATION.md#cvc>, (accessed March 6, 2024).
- [24] OSHWA, “Open Source Hardware Certification - TinyTapeout,” <https://certification.oshwa.org/es000040.html>, (accessed March 6, 2024).
- [25] M. Venn, “TT02 Silicon is Alive! - Zero to ASIC Course Blog,” <https://www.zerotoasiccourse.com/post/tt02-silicon-is-alive/>, (accessed March 6, 2024).
- [26] C. ‘whitequark’, “Amaranth,” <https://amaranth-lang.org/docs/amaranth/latest/>, (accessed March 6, 2024).
- [27] ChipsAlliance, “Chisel,” <https://www.chisel-lang.org/>, (accessed March 6, 2024).
- [28] M. Venn, “TinyTapeout 03p5 - GitHub Repository,” <https://github.com/TinyTapeout/tinytapeout-03p5>, (accessed March 6, 2024).
- [29] G. R. Limited, “MicroPython Official Website,” <https://micropython.org/>, (accessed March 6, 2024).
- [30] M. Venn, “Demo Firmware Test Script - TinyTapeout Repository,” <https://github.com/TinyTapeout/tt3p5-demo-fw/blob/main/tt3p5-test/test.py#L119>, (accessed March 6, 2024).
- [31] P. Deegan, “TT04+ Demoboard PCB - TinyTapeout Repository,” <https://github.com/TinyTapeout/tt-demo-pcb>, (accessed March 6, 2024).
- [32] L. Moser, “Pinouts Specifications - TinyTapeout,” <https://tinytapeout.com/specs/pinouts/>, (accessed March 6, 2024).
- [33] U. Shaked, “Awesome TinyTapeout PMODs - GitHub Repository,” <https://github.com/TinyTapeout/awesome-tinytapeout-pmods>, (accessed March 6, 2024).
- [34] Efabless, “Caravel Openframe Project,” https://github.com/efabless/caravel_openframe_project, (accessed March 6, 2024).
- [35] H. Pretl, “TT05 Analog Test,” <https://github.com/iic-jku/tt05-analog-test>, (accessed March 6, 2024).