Publishable Summary

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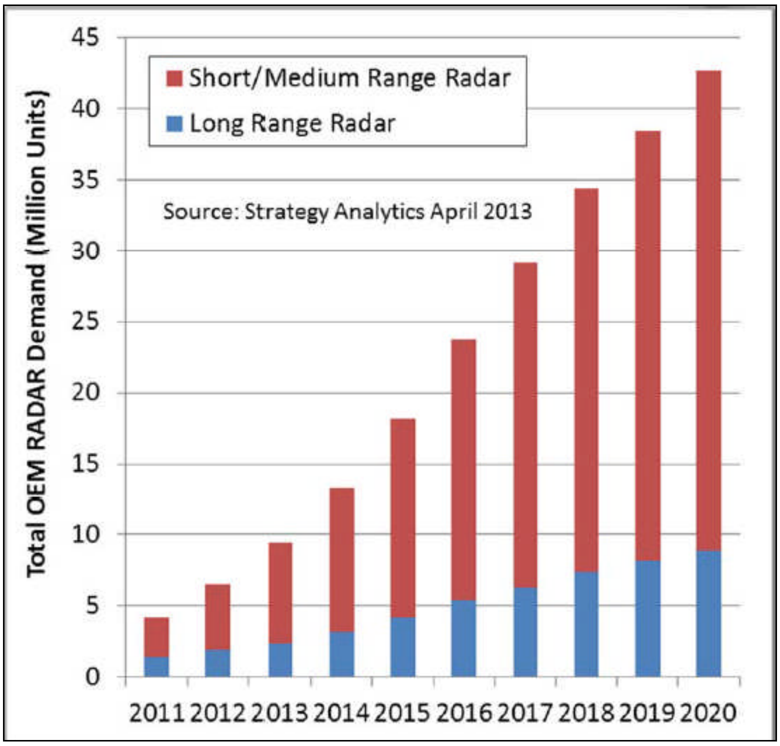
[1] Usually the contact person of the coordinator as specified in Art. 8.1. of the Grant Agreement.
[2] The home page of the website should contain the generic European flag and the FP7 logo which are available in electronic format at the Europa website (logo of the European flag: http://europa.eu/abc/symbols/emblem/index_en.htm logo of the 7th FP: http://ec.europa.eu/research/fp7/index_en.cfm?pg=logos). The area of activity of the project should also be mentioned.

Publishable summary

DOTSEVEN is a very ambitious 3.5 year R&D project targeting the development of silicon germanium (SiGe) hetero-junction bipolar transistor (HBT) technologies with cut-off frequencies (f_{max}) up to 0.7 THz. Special attention is also paid to clearly demonstrate manufacturability of the technology in standard CMOS fabrication environment and its suitability for BiCMOS integration at the 130nm node while still maintaining outstanding high frequency performance of around 0.5 THz, a performance level not reachable even with today's most advanced "stand-alone" CMOS processes at 28 nm and below. Thus DOTSEVEN will also impressively demonstrate the capabilities of lithographically much more relaxed "More than Moore" technologies like SiGe based BiCMOS. The results of the DOTSEVEN project will reinforce and further strengthen Europe's leading-edge position in SiGe HBT technology, modelling and SiGe enabled mm-wave applications and keep our related research and industrial activities significantly ahead of non-European competitors.

The capabilities and benefits of 0.7 THz SiGe bipolar and 0.5 THz BiCMOS technology will be demonstrated by numerous benchmark circuits and many system applications in the sub 0.1 to 1 THz range.

Automotive radar sensors working in the 76-81 GHz range and around 24 GHz constitute the largest civil market for highly integrated Silicon-based mmwave circuits today. It is also the market with the largest growth rate driven by the increasing demand for safer cars equipped with ADAS (Advanced Driver Assistance Systems) due to more stringent requirements for future EU-NCAP 5-star ratings (European New Car Assessment Program). A strong market growth is expected in this segment over the next years



What will even more push a broad deployment of high performance radar sensors in the automotive area on the long term is autonomous driving (AD). All big OEMs (VW/Audi, Daimler, Ford, GM, Toyota, Volvo and so on) have –partly triggered by Google's self-driving car- started development programs into AD and announced first cars with at least semi-automated or "piloted" driving capabilities like self-parking or self-driving in dense or jamming, low speed stop-and-go traffic as often found during rush-hours for around 2020. AD systems will have to be very reliable, robust and fail-safe which will imply utilization of 3-4 complementary sensors types (one speaks of fusion of radar, camera, lidar and possibly ultra-sonic sensors) of which at least two have to confirm simultaneously a dangerous situation to trigger an automatic action of the car. It implies also that in minimum 5-6 radar sensors per car (one at each corner and one at the middle of the front and rear area) will be needed to enable "surround" view from short to long distance around the car. Considering a total market of around 100 Mio units of new cars in 2020 and a market penetration of about 50% a demand of several hundreds of million radar sensors per year can be estimated.

High-speed wireless communication applications at 60 GHz and in the E-Band from 71-76 GHz and 81-86 GHz show large market potential too. Whereas this market is currently of limited size and mainly given by the chipset demand of wireless backhaul links, it might explode when future 5G cellular networks will require Gb/s connectivity built into the end user's cell phone. It is clear that only very power efficient mmwave transceivers will be suitable for that application and absolutely mandatory for utilization in mobile battery driven devices.

Even for radar MMICs not powered by small batteries, much lower power consumption and improved PAE (Power Added Efficiency) is urgently needed for faster market penetration and more ubiquitous deployment in safety critical applications. Severe problems connected to low PAE are:

- Higher fabrication cost (expensive measures for heat removal, costly full-metal sensor housings)
- Limited number of integrated RF channels and control functions
- And even with the limitations mentioned above today's sensors can only operate with low duty-cycles of typically 30%, which will not be acceptable in future safety critical applications like AEB (autonomous emergency braking).

Growth in automotive radar and wireless Gb/s communication markets can only be sustained with the availability of low cost, SiGe based high volume production processes. For these applications mature SiGe BiCMOS technologies with moderate logic gate count (i.e. 130 to 90 nm nodes) but much higher cut-off frequencies than today are required in the future. Sufficient design margins for robustness, high yield and lowest power consumption can only be guaranteed if intrinsic cut-off frequencies of the implemented SiGe HBTs are at least a factor of 5 times higher than the operating frequencies of the circuits which in our case implies minimum f_{max} values of 400 to 500 GHz. Typical f_{max} values of current production processes are ranging from 200 to 300 GHz. Especially the PAE and total power consumption of mmwave circuits will benefit tremendously from significantly higher f_{max} values.

With regard to these sub-100 GHz applications the targets of DOTSEVEN might appear as an overkill at the first glance, but to achieve 400 - 500 GHz (5 times $f_{operation}$) in high-volume production processes later-on under the constraints of CMOS integration and the requirements of sufficient process capability (6 sigma process windows) typical f_{max} values of 600 – 700 GHz should be demonstrated at minimum for the plain SiGe HBT device on laboratory level.

Another strong motivation of the DOTSEVEN project arises from the increasing interest in utilizing the mm-wave and sub-mmwave frequency spectrum above 0.1 THz and up to 1 THz for a wide variety of new "THz" applications. Here the need for very high speed transistors is more obvious.

Examples of THz applications are:

THz technology is an emerging field which has demonstrated a wide ranging potential. Extensive research during the last years has identified many attractive application areas and paved the technological paths towards broadly usable THz systems. THz technology is currently in a pivotal phase and will soon be in a position to radically expand our analytical capabilities via its intrinsic benefits. The rapidly increasing interest in THz-applications has most recently even spawned the start of a new IEEE Journal, namely the “Transactions on Terahertz Science and Technology”.

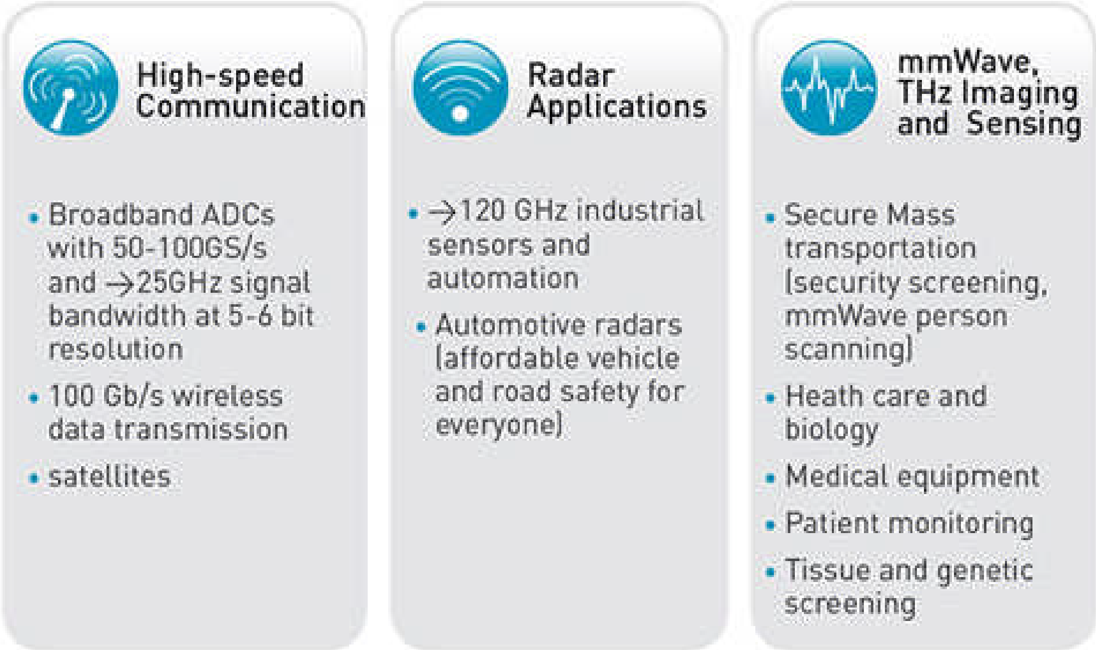


Illustration of mm-Wave and THz applications

Within DOTSEVEN it should be possible to realize high-speed circuits operating up to fundamental frequencies of 300 GHz and with utilization of higher harmonics (sub-harmonic operation) even up to the intrinsic cut-off frequency of the active devices and above. Due to the more explorative nature of these activities the requirements on design margins, low power consumption or yield are less demanding; the challenge lies here in succeeding to demonstrate the feasibility of the corresponding applications at all.

The main objectives of the DOTSEVEN project can be summarized as follows:

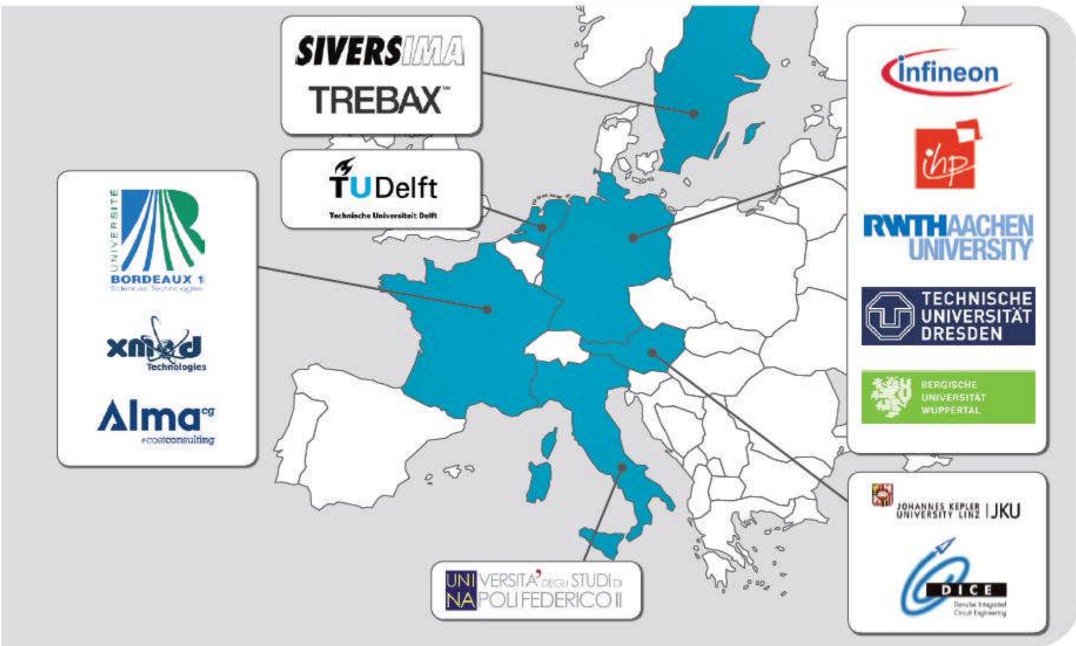
1. Realization of SiGe hetero-junction bipolar transistors (HBTs) operating at maximum unity power gain cut-off frequencies (f_{max}) in the 0.6 to 0.7 THz range.
2. Integration of these transistors into a manufacturable 130 nm BiCMOS process with f_{max} values in the 0.4 to 0.5 THz range.
3. Realization of high-speed circuits with fundamental operating frequencies up to 0.3 THz and sub-harmonic operation up to 1 THz.
4. Demonstration of the feasibility of radar and THz sensing and imaging applications in the 0.1 to 1 THz range.
5. Demonstration of the feasibility of wireless communication links with data rates in the 100 Gb/s range.

6. Demonstration of significant power savings for automotive radar applications below 0.1 THz.
7. Evaluation, understanding and modelling of the relevant physical effects occurring in such high-speed devices and circuits.

The results of this project are expected to be the last stepping stone before realizing a SiGe HBT with THz performance.

Much more important is the beneficial impact of DOTSEVEN on already maturing sub-0.1 THz applications like automotive radar and wireless Gb/s communications, where Europe’s automobile, communication and semiconductor industry plays already a worldwide leading role. The outcome of the project will significantly enhance Europe’s process capabilities in advanced SiGe BiCMOS processes and secure the local supply of cost- and power-efficient SiGe mmwave products of outstanding performance.

A highly qualified and success-proven consortium of 14 partners, from industry and academia in 6 European countries, has been set-up to achieve these goals.



The project has a scheduled duration of 42 months and runs from October 2012 until March 2016.

Up to now (January 2015) the project as a whole has made very good progress in reaching its goals. Overviews of results were given at an open workshop at the BCTM 2013 conference in Bordeaux (Workshop@BCTM 2013) and during a THz workshop at the ESSCIRC/ESSDERC Conference in 2014.

Three different SiGe HBT architectures are currently being investigated. A downscaled conventional Double-Polysilicon Self-Aligned (DPSA) transistor with Selective Epitaxially Grown (SEG) base (DPSA-SEG HBT) was chosen by IFAG as basic architecture for the development of a 400 GHz / 130 nm BiCMOS technology platform.

Two more advanced DPSA HBT concepts developed by IHP utilize an epitaxial Elevated External Base-contact (EEB) with a Non-Selective Epitaxially Grown (NSEG) base (DPSA-NSEG EEB transistor) or a selective Epitaxial Base-Link (EBL) concept in conjunction with a SEG base (DPSA-SEG EBL transistor), respectively. The EEB and EBL architectures have been chosen as starting points for the development of the 0.7 THz technology.

Additionally, common investigations are undertaken by IHP and IFAG to evaluate the performance limits of the EBL emitter / base module in IFAG's 130 nm BiCMOS environment. Here f_T / f_{max} values of 300 GHz and 500 GHz, respectively, are targeted.

At this point in time, the second and final fabrication cycle of mmwave demonstrator circuits and test structures for methodology development and model calibration is being prepared based on the results of the first fabrication run and short cycle experimental runs.

On our way towards 0.7 THz transistors we have thoroughly characterized 570 GHz HBTs from the first IHP fabrication run with an optimized vertically and laterally shrunk EEB structure. At shorter emitter length these transistors even reach f_{max} values of 600 GHz. Furthermore, 490 GHz HBTs based on IHPs EBL concept have been successfully integrated into an existing, industrial 130 nm CMOS process and all relevant additional devices for a full BiCMOS PDK have been characterized.

A lot of effort has been put into improving the accuracy of SiGe HBT modelling and the understanding of physical effects. There were still large discrepancies between measured device parameters and those predicted by device simulation. As these discrepancies must not necessarily be caused by "wrong" models but could also be caused by measurement inaccuracies of the physical device parameters (e.g. doping profiles, device geometries etc...) many experiments were undertaken for device simulation related model calibrations. Several improvements have also been made to the compact model used for circuit design simulation, and a thorough model verification effort, including thermal effects and benchmark circuits, is under way. Also, reliability studies have been started.

IFAG's 130 nm / 400 GHz BiCMOS (B11HFC) and IHP's 130 nm / 500 GHz BiCMOS (SG13G2) process platforms were used for the first circuit runs. Circuit results from these runs have been presented at the RFIC / IMS (June 2014), EuMW (October 2014) and in a THz workshop at the ESSCIRC/ESSDERC Conference (September 2014). In summary record frequencies of operation and RF performance for Silicon-based mmwave circuits have been demonstrated:

- LNAs up to 233 GHz with 19 dB 23 dB gain
- Power amplifiers up to 240 GHz with 5 dBm output power
- Frequency multipliers (x16) up to 265 GHz with 2 dBm output power
- I/Q TX / RX communication chip set at 240 GHz with a usable bandwidth of 65 GHz (SNR > 10 dB)
- Static frequency dividers up to 160 GHz (world record for Si-based circuits)

Power consumption of a 77 GHz 3 Ch- radar transmitter with 3 x 14 dBm output power reduced by more than 40% compared to present state of the art technology

Latest results, announcements, information about dissemination activities, publication links and other useful information about DOTSEVEN can be found on our website www.dotseven.eu.

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